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Acoustic Tomography for Decay Detection in Red Oak Trees

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Abstract

The science of tree stability analysis uses both biological and engineering principles in attempting to rate a tree's structural soundness and make reasonable predictions of potential for failure. In such analysis, arborists are often challenged by internal structural defects hidden from view within the trunks. This paper reports the results of an investigation using acoustic tomography to detect internal decay in park trees. Two century-old red oak (*Quercus rubra*) trees located at the Capitol Park in Madison, Wisconsin, were nondestructively evaluated using an acoustic tomography technique. The trees were subsequently felled, and a disk at each test location was obtained and examined. We found that the light-colored zones in the tomograms were larger than the true decay present in the disks. The oversized light-colored areas were the composite effects of both decay and large internal cracks. The results of this study demonstrated that acoustic tomograhy cannot distinguish between large internal cracks and heartwood decay. To make a better assessment of internal condition for urban trees, resistance microdrilling should also be used prior to tree removal.

Keywords: acoustic tomography, crack, decay, tree stability.

Contents

Page

Introduction 1
Materials and Methods 1
Results 2
  Red Oak Tree #307 2
  Red Oak Tree #123 3
Discussion 3
  Geometry of Cross Section 3
  Interpretation of Tomograms 3
  Verification of Tomograms 5
Conclusion 6
Literature Cited 7

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Acoustic Tomography for Decay Detection in Red Oak Trees

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Introduction

Within an urban community, trees are valuable assets providing ecological, aesthetic, social, and economic benefits. With the proximity of people and property to tall, massive trees, it is important to manage the risk of tree failure by measuring physical characteristics for signs of instability. The science of tree stability analysis uses both biological and engineering principles in attempting to rate a tree's structural soundness and make reasonable predictions of potential for failure. In such analysis, arborists are often challenged by internal structural defects hidden from view within the trunks. Although arborists have used visual tree assessment as an essential practice in the past, visual assessment is not always sufficient and cannot provide true information that determines trees' condition and stability. Concerns about public safety and urban forest conservation support developing and applying more rapid and precise diagnostic technologies to detect decay and other types of structural defects in trees, particularly in the lower portion of the stems.

The use of stress waves (ultrasound or sound waves) to detect decay in trees has been explored by many researchers (McCracken 1985; Mattheck and Bethge 1993; Yamamoto and others 1998; Lin and others 2000; Wang and others 2004). The concept of detecting decay using this method is based on the observation that stress-wave propagation is sensitive to the presence of degradation in wood. Stress-wave velocity is directly related to the physical and mechanical properties of wood. In general terms, stress waves travel more slowly in decayed or deteriorated wood than they do in sound wood. They also travel around hollows, increasing the transmission time between two testing points. The first generation stress-wave equipment used for decay detection was two-probe systems that measured the wave transmission time in a single path. The capability of a single-path approach for tree-decay detection has proven to be limited because stress-wave velocity across tree stems varies substantially even for intact trees, and a standard reference velocity for data interpretation is not readily available (Wang and others 2005).

In recent years, tomography techniques that were developed for engineering or medical applications have been evaluated for their applicability in standing trees. Investigations on urban trees showed a great success of using tomography techniques to detect internal decay. Nicolotti and others (2003) applied three different types of tomography methods (electric, ultrasonic, and georadar) to urban trees and found different degrees of success. Of the three technologies evaluated, ultrasonic tomography proved to be the most effective tool for detecting internal decay, locating the position of the anomalies and estimating their sizes, shapes, and characteristics in terms of mechanical properties.

Gilbert and Smiley (2004) evaluated an acoustic tomography tool for its ability to quantify decay in white oak (*Quercus alba*) and hickory (*Carya* spp.). PiCUS tomography (Argus Electronic Gmbh, Rostock, Germany) and visual inspection were used to evaluate 27 cross sections from 13 trees. Gilbert and Smiley reported a high correlation between the amount of decay detected by the PiCUS and the amount actually present in the cross sections ($r^2 = 0.94$) for all cross sections. The average percentage accuracy for samples where decay was present was 89%. No cracks were present in the trees they tested.

This paper reports the results of a recent park tree inspection project and addresses some technical issues in using acoustic tomography to detect internal defects in century-old red oak trees.

Materials and Methods

Two red oak (*Quercus rubra*) park trees were nondestructively tested using an acoustic-based tomography technique to obtain two-dimensional tomograms of the cross sections of the lower stems. The trees were located at the Capitol

Table 1. Dimension and visual observations of two red oak trees tested

Tree number	DBH[a] (cm)	Height (m)	Crown spread (m)	Visual observations
Red oak #123	269	14.6	11.4	*Root collar*: lacks defined buttress roots and valleys; bulging indicates decay.
				Trunk: bulging ribs and cracks; cankers on south side with a surface-strata fungal growth extending up trunk.
				Crown: less than 15% of the crown remains, with continuing tip dieback and large branch death.
Red oak #307	345	16.5	17.3	*Root collar*: lacks taper and well-defined roots, indicating decay.
				Trunk: indented ribs and fungal conks on west side; bulging rib with fungal conks on east side.
				Crown: triple scaffold limb attachment at actual angle; pruning wounds and bend in upright upper canopy branches.

[a] Diameter at breast height.

Park in Madison, Wisconsin. According to the historical documentation, these trees were planted between 1907 and 1918, along with the rest of the park trees in the Capitol Park (Allison 2005).

A visual tree inspection was conducted before acoustic testing to document visual signs of structural instability. The trunk circumference at breast height, tree height, and crown spread of the trees were also measured or estimated using basic forest survey tools (steel tape, clinometer, and measuring wheel). Table 1 summarizes the dimensions and physical observations of the trees.

Following visual inspection, a PiCUS Sonic Tomograph tool was used to conduct acoustic tomograph measurements on the trees. The PiCUS Sonic Tomogroph measurement system consisted of 12 sensors evenly placed around the trunk in a horizontal plane during testing (Fig. 1). Each sensor was magnetically attached to a pin that was tapped into the bark and sapwood. Acoustic wave transmission data were collected by sequentially tapping each pin using the steel hammer. A complete data matrix was obtained through this measurement process at each testing location.

The tomograph measurement was conducted at one elevation (100 cm above ground) for tree #123 and at three elevations (10 cm, 100 cm, and 200 cm above ground) for tree #307. At each elevation, the circumference and distances between sensors were measured using a tape measure and a PiCUS caliper. This information was used as an input for the system software to map the approximate geometric form of the cross sections. Because the cross sections of the oak trees tested were irregular, we selected the “free geometry” feature of the program to reconstruct the geometry of the cross sections.

Upon completion of acoustic measurements, a tomogram was constructed for each cross section using the PiCUS Q70 software. For tree #307, a three-dimensional tomogram was also constructed based on the tomograph measurements at three elevations (10 cm, 100 cm, and 200 cm).

Following field acoustic tomograph measurements, trees were felled and a 10- to 15-cm-thick disk was cut from each elevation. All the disks were then transported to the Forest Products Laboratory (FPL) for physical examination and laboratory acoustic measurements. A digital picture of the cross section was also taken for each disk.

Results

Red Oak Tree #307

After being cut down, tree #307 was found to have heartwood decay at all three elevations. Laboratory examination confirmed the presence of white-rot decaying fungus. The decay was less severe in the upper cross section (200-cm elevation), but it increased as the elevation dropped. The decay was so extensive at the base section that part of the interior decayed wood fell off when the lower disk (10-cm elevation) was removed from the tree butt.

In addition to decay, major internal cracks were present in the cross sections of tree #307. The combination of extensive decay and large lateral cracks caused the base disk to fall into several pieces during transportation. The photographs of the disks show that lower and middle cross sections had multiple lateral cracks and the upper cross section had one large lateral crack.

Figure 2 shows comparisons of acoustic tomograms with photographs of the cross sections at three elevations. In the tomograms, the cross section was mapped into different color zones based on the distribution of acoustic velocities measured using the PiCUS tool. The dark-colored zones in the tomograms represent solid wood, and the light-colored zones represent decayed wood (the tomograms used green, violet, and blue to represent increasing degradation by decay). The tomograms clearly show a strong correspondence to the images of the disks. Extensive decay and radiating lateral cracks in the lower and middle cross sections were reflected by large light-color zones in the tomograms. The tomogram of the upper cross section accurately located the

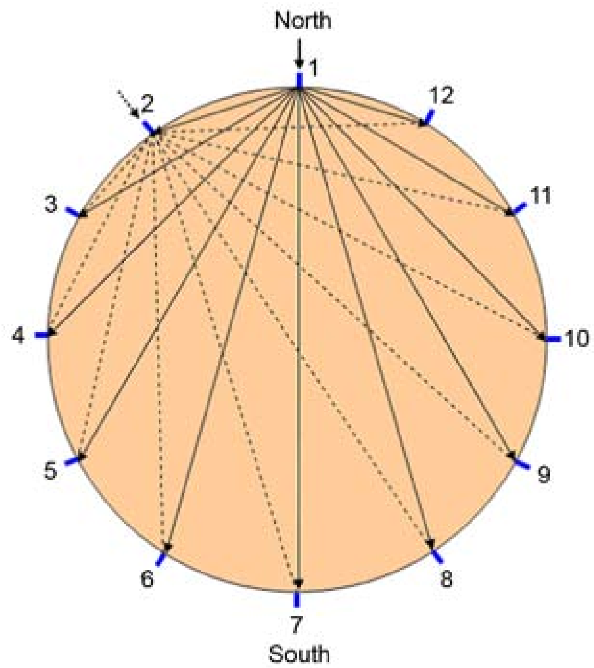


Figure 1. Sensor arrangement on a tree trunk for acoustic tomography measurement on trees.

position and orientation of the big lateral crack and heartwood decay.

Figure 3 is a three-dimensional tomogram of tree #307 that demonstrates the progressive changes of decay and macroscopic defects at different elevations. This clearly matches the transition of decay and cracks found in the disks. The massive rot at the lower part of the trunk indicated by light-colored zones in the tomograms supported our speculation that decay fungus originated from the root system. Root excavation to 30-cm depth at root collar revealed a lack of identifiable primary roots and a very heavy fibrous mat of adventitious roots closest to the trunk.

Red Oak Tree #123

Figure 4 shows the comparison of acoustic tomogram with a photograph of the cross section for tree #123. The tomogram at 100-cm elevation showed a large light-colored area with an elliptical shape, suggesting extensive heartwood decay in the cross section. Subsequent resistance microdrilling into the cross section from the south side revealed a minimal depth of 38 cm into a cavity (Fig. 5). These observations seemed to support a conclusion that the lower stem of the tree had a serious internal decay problem. However, the cross-section image of the disk indicated otherwise. It was the big “snake” (S-shaped) crack, not the extensive heartwood decay, that triggered the large decay-indicating light-colored zones in the tomogram. Even the single microdrilling into the tree trunk at 100-cm elevation gave misleading information (decay positive) because the drill happened to be driven into the long snake crack, thus resulting in zero resistance in the profile chart (Fig. 5).

Discussion

Geometry of Cross Section

PiCUS Q70 Software offers two options to measure the geometry of the tree cross sections: (1) ellipse, and (2) free shapes. Considering the complexity of the trunk shape for the red oak trees tested, we selected free shapes mode to construct the geometrical boundary for the tomograms. The distances between sensors were measured and input into a computer following the one-baseline system (Argus Electronic Gmbh 2003). Because the determination of acoustic velocity is based on both sound transmission time and travel path, it is critical to accurately measure the distances between the sensors. The PiCUS electronic caliper was extremely helpful in achieving this goal, especially for trees with large diameters.

The geometries of the tree cross sections constructed using the PiCUS software generally conformed to the shapes of the trunks. However, most bulges observed on the red oak trees were not reflected on the tomograms. The structural details of the trunk surfaces were smoothed out due to large distances between adjacent sensors (22 to 29 cm). This geometry imperfection did not seem to have a significant effect on detecting internal defects in this case because the major problem areas were in heartwood and spanned across the diameter, as was seen in the tomograms. However, if sapwood decay or any other macroscopic abnormalities near the trunk surface became dominating defects, the tomogram quality could be affected. It would be beneficial to strategically place more sensors on the critical area of a trunk to improve the local resolution if the surface or near-surface defects constituted a concern to the stability of a tree.

Interpretation of Tomograms

The acoustic tomograms obtained using the PiCUS Sonic Tomograph provided strong evidence of structural instability in both trees. The defect areas identified by the tomograms were large at all locations, which showed strong correspondence to true physical conditions of the cross sections (Figs. 2 and 4). In fact, the decision to remove these two trees from the Capital Park was made based on this supporting evidence (Allison 2005).

By comparing the tomograms with corresponding cross-section photographs, we found that most decay pockets in the cross sections were displayed in the tomograms as green, violet, and blue, depending on the severity of the decay. However, the light-colored decay zones shown in the tomograms were apparently larger than the true decay areas presented in the cross sections. Examination of the cross sections revealed that internal cracks (star crack, snake crack, lateral crack) were also the dominating defects in these two red oak trees. These cracks, mostly presented in the radial direction and extended up and down in vertical planes within the trunk, effectively cut off linear propagation of the acoustic waves and caused the waves to follow

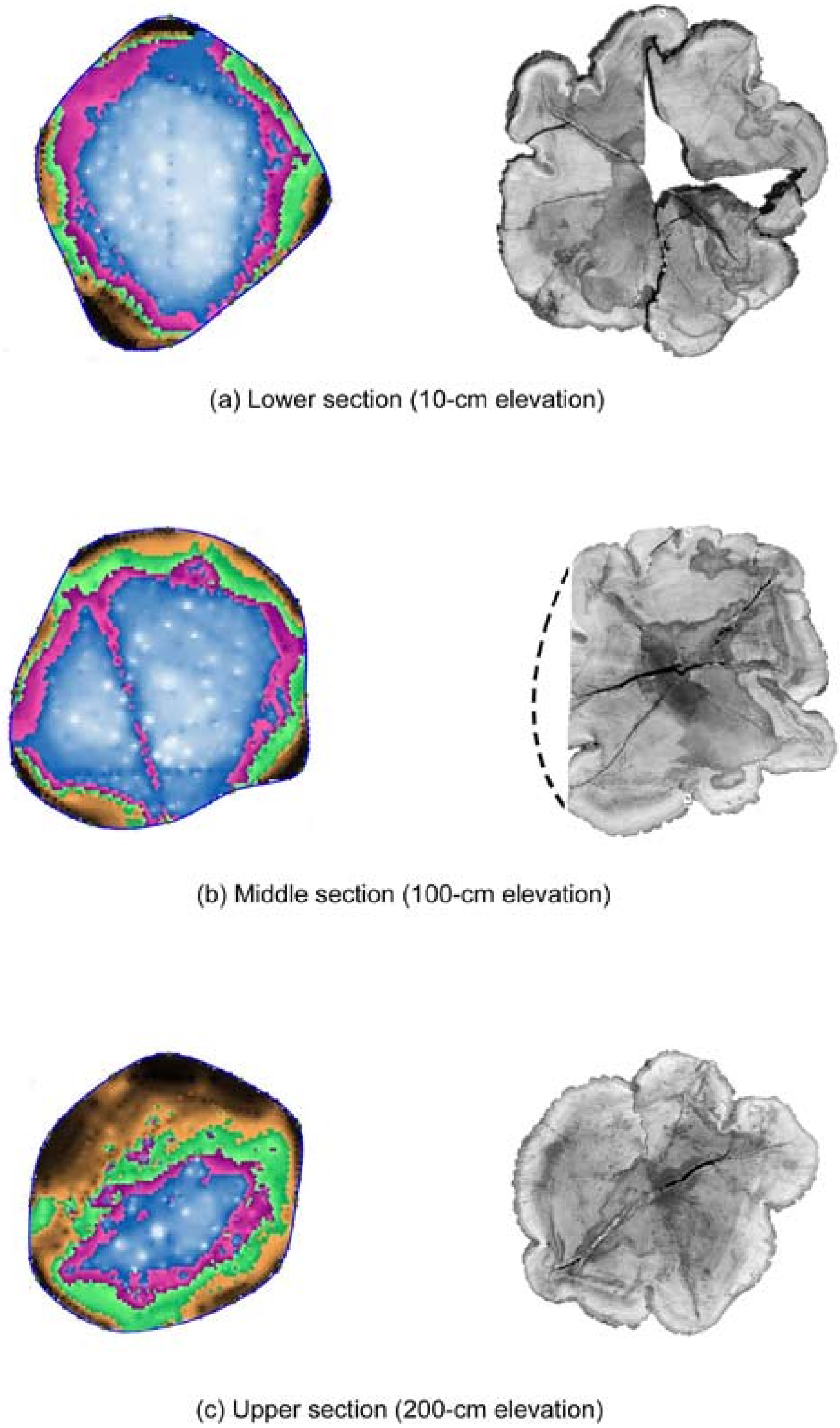


Figure 2. Comparison of acoustic tomograms with photographs of corresponding cross sections for red oak tree #307.

Figure 3. Three-dimensional tomogram for red oak tree #307.

a much longer travel path. The direct result of this was that even without decay presence, the software produced a big "fat" light-colored zone in the tomograms that resembled the influence of extensive heartwood decay. Therefore, the tomograms generated using the PiCUS software were the composite effects of both decay and cracks. Consequently, the light-colored zones cannot be simply interpreted as heartwood decay.

When large cracks are the dominating defects in the cross section, the light-colored zones tended to be much wider than the crack. Especially when star-shaped cracks or snake-shaped cracks are present, tomograms tend to show large light-colored "decay shadows," which are quite misleading. This crack effect can be attributed to (1) limited resolution associated with acoustic approach (signal wavelengths are not adequate to the resolution needed) and (2) limited sensors placed around a tree trunk, especially for old park trees with large diameters. For acoustic tomography, the most effective way to increase spatial resolution of the tomograms is to reduce the distance between adjacent sensors.

The two red oak trees we tested in this project had a circumference of 269 cm (tree #123) and 345 cm (tree #307), which is equivalent to an average diameter of 86 cm (tree #123) and 110 cm (tree #307), assuming a round shape. During field measurements on the trees, we used all 12 sensors available for each tomogram. The distance between adjacent sensors was about 22 to 29 cm. After trees were felled, we employed a different sensor arrangement to reconstruct tomograms from the disk of tree #123. In this laboratory evaluation, we reduced the distance between adjacent sensors in half by placing all 12 sensors at one half side of the disk each time (Fig. 6a). By measuring two half disks (east half and west half), we constructed two half tomograms for the cross section. Figure 6b shows the image of two half tomograms combined together, representing the complete cross section of the disk.

Comparing two half tomograms taken on the disk to the tomogram taken on the tree, we found that the light-colored decay shadow was not thinned as the distance between adjacent sensors reduced. Overall, the decay shadow in the combined two half tomograms matches the shadow in a single tomogram taken on the tree. This indicated that the crack effect might not be a resolution problem and cannot be solved by just increasing the number of sensors placed on the trees.

Verification of Tomograms

The results of this study have profound meaning to decay detection in urban trees. Acoustic tomography techniques have proven to be effective in many case studies for decay detection and locating with accuracy the size and location of internal decay. However, our results indicate that these techniques are not able to distinguish between large internal cracks and heartwood decay. To make better assessment of internal conditions for urban trees, other approaches such as visual inspection and resistance microdrilling should also be employed to provide supporting evidence whenever it is necessary.

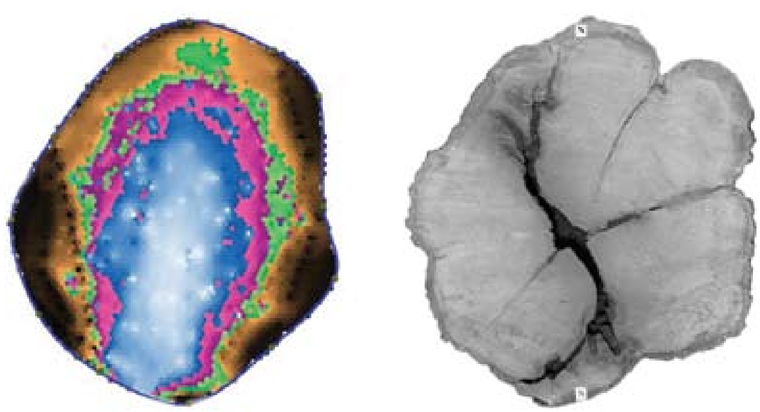


Figure 4. Comparison of acoustic tomogram and photograph of the cross section for red oak tree #123.

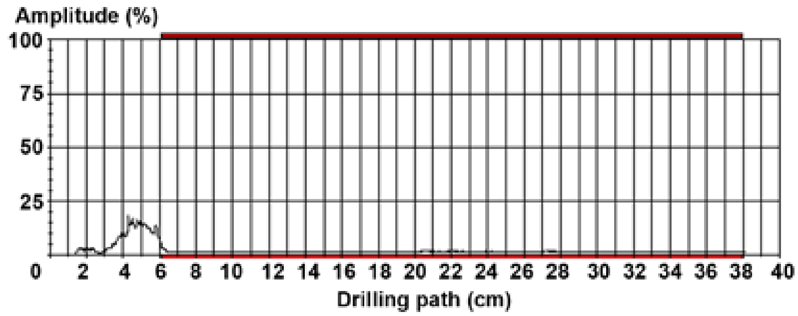
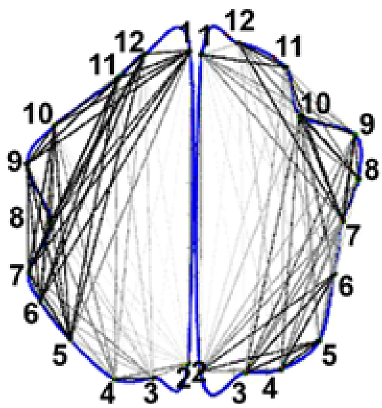
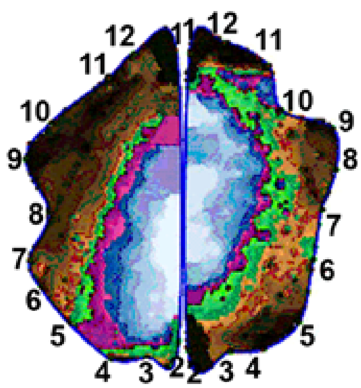


Figure 5. Resistance profile for red oak tree #123 (microdrilling into the tree trunk at 100-cm elevation from the south side).



(a) Sensor arrangement on east half and west half of the cross section



(b) Two half tomograms combined together

Figure 6. Two half tomograms for red oak tree #123 at 100-cm elevation.

Take tree #123 as an example. The tomogram at 100-cm elevation showed possible extensive heartwood decay within the trunk. The light-color zone was in an elliptical shape and extended to the south edge. Visual inspection indicated bulging ribs and cracks on the south side with a surface strata fungal growth extending up the trunk. It seems that either decay or crack could be the dominating defect. To verify the nature of this light-color zone, the inspector could conduct resistance microdrilling testing at several locations near the suspect decay area. Figure 7 shows the resistance profile charts obtained using the IML-Resi measuring instrument (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany) from three drilling locations (A, B, and C) in the south side of the tree. The resistance profiles indicated only minor cavities (3 to 5 cm) at these drilling paths, and most parts were actually solid. This suggested that large light-colored areas in the tomogram were primarily caused by big cracks oriented in north–south direction.

Conclusions

Two century-old red oak trees located at the Capitol Park in Madison, Wisconsin, were nondestructively evaluated using an acoustic tomography technique. A two-dimensional tomogram was constructed for each cross section using the PiCUS Q70 software. We found that light-colored decay zones shown in the tomograms were much larger than the actual decay areas presented in the disks cut from the test locations. Close examination of the cross sections indicated that the oversized light-colored areas were the composite effects of both decay and large internal cracks. The results of this study demonstrated that acoustic tomography would not distinguish between large internal cracks and heartwood decay. To make better assessment of internal condition for urban trees, other approaches such as visual inspection and resistance microdrilling should also be employed to provide supporting evidence.

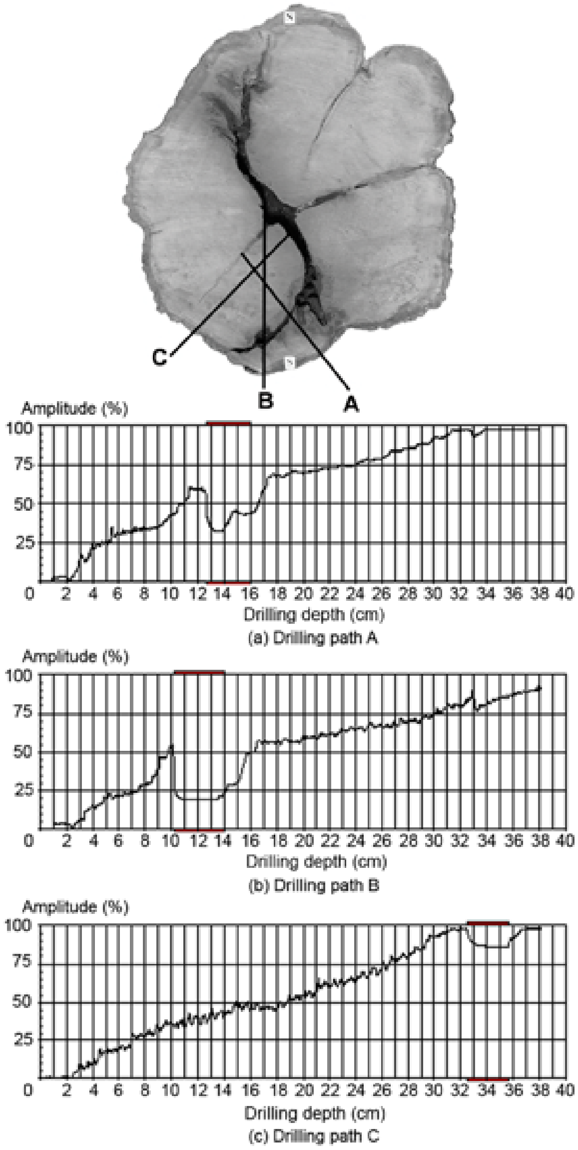


Figure 7. Resistance profile for verifying the tomogram of red oak tree #123 at 100-cm elevation. A, B, and C show the drilling path orientations.

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