How Sensor Positioning Influences Sonic Tomography Results

Frank Rinn

INTRODUCTION

My motivation for developing sonic tomography (Rinn 1999) was triggered by the inappropriate use of resistance drilling, and the subsequent erroneous pro-files that were generated (**Fig. 1**). Originally, I developed resistance drilling as a dendrochronology tool used to reconstruct climatic data recorded in tree ring density variability (Rinn 1988; Rinn et. al 1989). The method's potential for detecting decay in living trees was realized after initial tests (Rinn 1989), but only valid for calibratable resistance drills with a high and linear correlation to wood density. Various non-calibrated resistance drills, later promoted by some scientists for evaluation of tree safety, were found to produce highly inaccurate results (Rinn 2017b) and not reliably detecting decay (**Fig. 2**). Furthermore, the VTA tree-stability-evaluation-procedures recommended at the time (drilling between the buttresses) were later shown to be inappropriate for evaluating the relative safety of the typical mature urban tree (Rinn 2018).

As a result of misleading profiles produced by many of the available drills, safe trees were removed or subjected to severe crown reduction (Rinn 2017b); this was compounded by unsupported recommendations to drill between buttresses (**Fig. 1a-b**). After felling, it often turned out that the trunk base was intact, or only had insignificant decay. Arborists started using the catchphrase "drilling kills trees," although it was not the drilling that harmed the tree but the inappropriate application (drilling between the buttresses and generating erroneous profiles).

In consequence, arborists around the world began demanding an affordable and non-destructive method to visualize wood conditions within a cross-section of the whole trunk - not just along a drilling path. While the modulus of elasticity could be estimated for wood fibers along the longitudinal axis using single-path stress-wave timing (Bertholf 1965), Pellerin et al. (1985) applied that "single-path" principle perpendicularly to the wood fibers to detect defects.

Although 'single path' sonic assessments quickly test for decay in many simple cases, they cannot provide the information required to determine wood condition in mature urban trees with complex cross-sections. The cross-sections of most mature urban trees are not circular, and internal defects are often off-center, as their roots and lower trunks are more subject to damage (**Fig. 1c-d**). This is why one would have to do multiple single path sonic measurements at the same cross-section, and then combine the results manually in a tomography-like sketch. This process takes hours for each cross-section, so it is not an economical approach. To streamline this process, we connected a chain of multiple sensors around the tree's circumference to generate a single-step tomographic assessment.

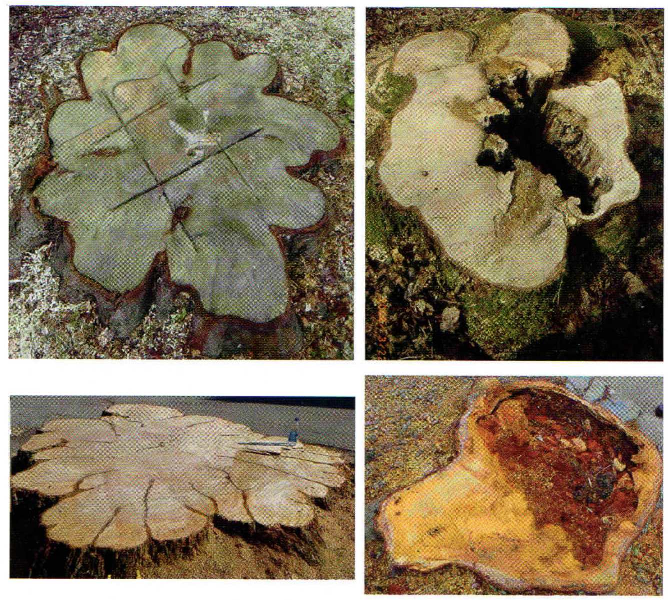

Figure 1. Two reasons why resistance drilling between buttresses (as frequently recommended) is not appropriate for the risk assessment of many older urban trees. First, included bark leads to low drilling resistance, easily misinterpreted as indicating decay (a-b). Second, cross-sections are usually not circular and defects are located off-center (c-d), so that local shell-wall (not only between buttresses) does not allow for a determination of the loss in load-carrying capacity due to defects. Included bark, in addition, may lead to erroneous interpretation of sonic tomography when the sensors are placed too low at the trunk flare.

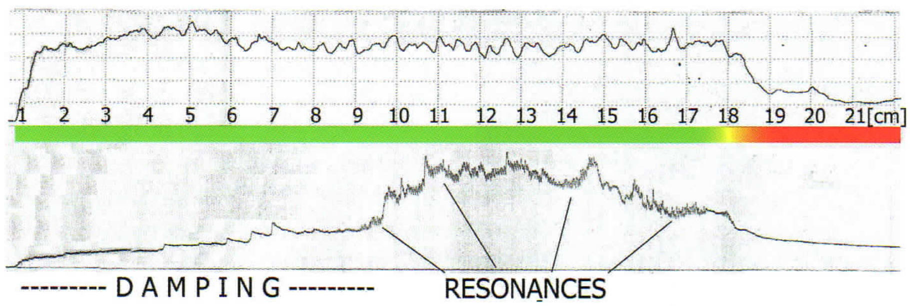

Figure 2. Two different radial profiles obtained at the same spot of a tree by different resistance drilling devices (x-axis = drilling depth: 21cm≈8 inches). The top profile was recorded by a high-resolution (10 Bit @ 25 points/mm ≈ 635dpi), electronically regulated drill, providing data clearly correlated with wood density (r^2>0.8) ad thus correctly revealing tree-ring density variations along the drilling path. Differences between intact (green) and decayed wood (red) are clearly visible, even incipient stages of deterioration (yellow-orange) in the transition zone. The bottom profile was obtained from a drilling device with mechanical recording of the penetration resistance (by using a spring loaded gear box): unavoidable damping and resonance effects of the spring mechanism systematically create erroneous and misleading profiles, either too low (putatively indicating decay) or over-emphasizing variances. It's obviously impossible to correctly evaluate wood condition based on the bottom profile.

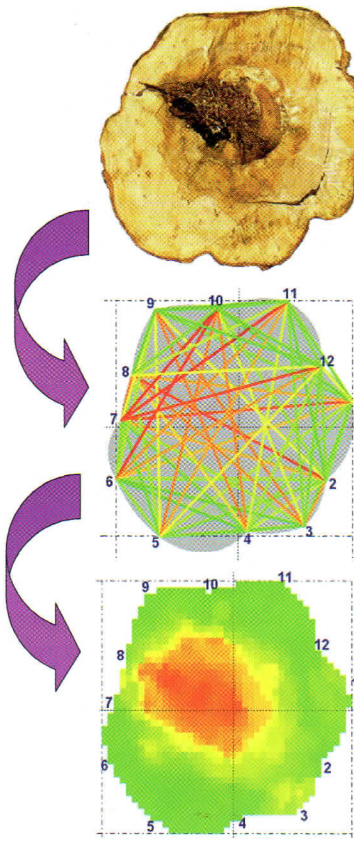

Figure 3. Commonly, the direct distance between the sonic sensors is divided by the measured time-of-flight and this virtual speed is visualized by using different colors: green for the highest, red for low speed values. The red lines, however, do not represent the travel path of the measured waves because they made a detour around a defect. In this kind of sonic tomography, invented in 1999, the arrival time of the quickest arriving signals is measured and these waves typically travel on a detour through the intact parts of the cross-section, thus around defects.

Due to the complex transmission pattern of sound waves in anisotropic materials like wood (Crampin 1984), we used only the time-of-flight ("ToF") of the fastest stress waves arriving at the receiving sensors for creating the sonic tomogram picture (**Fig. 3**) instead of the wave transient as commonly used in ultra-sound analysis for tree decay detection (Brandt 1987).

Since its first demonstration in 1999, more than 1000 risk assessors around the world now use mobile ToF sonic tomography for inspecting and evaluating potential tree trunk breakage. Although the physical principle of the different kinds of sonic tomography devices is similar, there are significant differences in usability, flexibility in sensor and cable exchange, and number, distance, and positioning of sensors. Of greater importance, though, are differences in the computational software built into the device, especially the mathematical algorithm that transforms the measured data into a colored picture. These differences have significant consequences for practical application, such as the required accuracy for measuring the position of the sensors. As one might expect, this affects the time required for an inspection. This may explain why the most frequently asked question in our sonic tomography workshops is "How precisely do you have to measure sensor positions?" The following discussion focuses on the sensor positioning accuracy required by the first and original sonic tree tomography device (Arbotom®) patented in 1999.

MEASUREMENT BASICS AND PRINCIPLES

When determining the breakage risk of mature urban trees with defects, the primary goal is to determine the loss of load-carrying capacity. This requires that the major cross-sectional sizes and shapes have to be recorded, because trunk diameter is the dominating factor determining the load-carrying capacity for a particular loading direction (Rinn 2011). Consequently, sonic sensors should be placed on or slightly above all major root buttresses, because these points commonly represent the outermost positions of the trunk base cross-sections.

Typically, sensors are placed within the flared trunk base because decay in most mature urban trees is initiated by injuries to the lateral roots. Placing the sensors too close to the ground can generate erroneous data, because included bark between the root buttresses (**Fig. 1**) inhibits

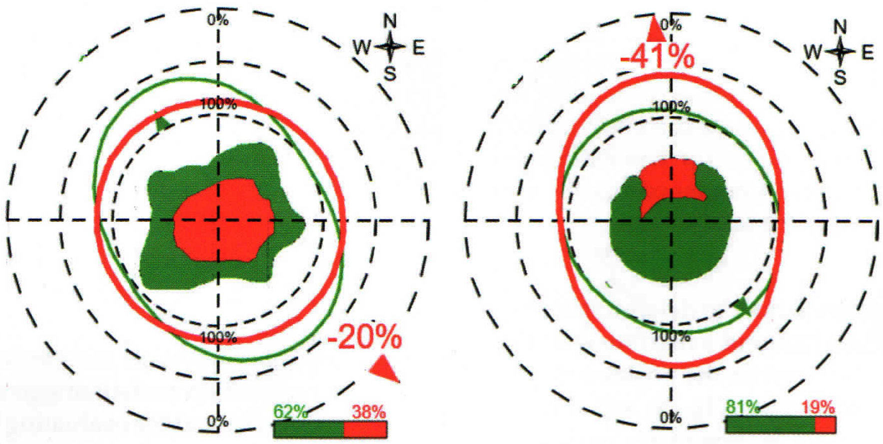

Figure 4. Two stem base cross sections showing decay pattern (red) typical for urban trees. The red curve around the cross-section represents the relative loss in load-carrying-capacity (Rinn 2011) largely given by the modified section modulus (Spatz & Niklas 2013). The red number near the red arrow shows the maximum loss in load-carrying-capacity caused by the defect - in comparison to the fully intact cross-section. In the left cross-section, 38% of the area is decayed, leading to a loss in load-carrying-capacity of approximately 20%. The right cross-section shows an off-center defect, typical for damages at the stem base by cars, and root pruning. In this case, approximately 19% of the cross-sectional area is decayed, but this leads to a loss in load-carrying-capacity of approximately 41%. This shows that the location of a defect in the cross-section is more important in terms of load carrying capacity as compared to the size of defects: smaller defects at the perimeter of the cross-section can lead to a bigger loss in load-carrying-capacity as compared to big defects in the center area.

the direct wave transmission similar to that as tree defects, potentially leading to flawed conclusions on tree stability. Consequently, the sensors should be placed slightly above the included bark zone.

When a sensor is tapped with an ordinary hammer, a microsecond-timer is electronically switched on within all sensors around the cross-section. As soon as the vibration (sound wave) caused by the tap and, spreading through the cross-section, arrives at a receiving sensor, the receiving sensor-electronics stops its internal timer. In this way,

Figure 5. A tape measure around the stem cross-section allows to measure the position of each sensor easily with an accuracy of ±1cm (±0.4").

the 'times of flight' of the fastest sound waves between the sending and receiving sensors is measured. When direct distance between these timers is divided by this time of flight, this produces a speed value and is represented as colored lines (**Fig. 3**). This procedure is repeated for each sensor.

If the wood between the sending and receiving sensors is fully intact, the fastest sound waves travel in a nearly straight line between them. Dividing the distance between two sensors by the measured time-of-flight in this case represents the real sonic speed of the wave between the two sensors. If there is a significant defect somewhere along this straight path between the sending and receiving sensor, however, the sound wave arriving first at the receiving sensor took an unknown detour (Rinn 2014). The larger the defect, the longer the detour and the higher the measured value (time-of-flight). When the direct distance between the corresponding sensors is divided by this time-of-flight, the resulting speed is lower but designated as 'virtual' because the length of the real travel path in a cross sections with internal defects is generally and principally unknown. Although these kinds of virtual speeds are only approximations, the values can be used to determine the most useful feature of the application: the relative loss in load-carrying capacity of a cross-section due to a defect, compared with that of the fully intact cross-section (Rinn 2015, 2017: **Fig. 4**).

Therefore, the key advantage of sonic tomography in evaluating the stability of mature urban trees is the determination of the relative loss in load-carrying capacity due to defects. This is far more important than the colored picture (="tomogram"), because these aspects can be misleading (**Fig. 4**) in evaluating tree safety.

SENSOR POSITIONING

There are various options in how to determine the position of sonic sensors placed around a tree cross-section: a simple and quick way is to record the position of each sensor along a circumference tape (**Fig. 5**) and then estimate its radial distance from an imaginary circle (**Fig. 6**). Recording two numbers per sensor this way usually takes a few minutes for most trees and does not need any additional tools. Typically, we need less than 15 minutes for such an inspection.

Alternatively, a specially designed caliper can be used to determine distances between several sensor pairs (**Fig. 7**) for reconstructing the geometry by triangulation (Fournier & Montuno 1984). But this takes more time and requires a specialized tool. Unfortunately, the standard calipers commonly used in forestry are not large enough to measure the distances involved in heritage trees, and it is difficult to assess sensors positioned between or behind large buttresses. Electronic calipers designed for this application are commonly connected wirelessly to the portable computer collecting the data for the tomography. They are costly and the whole process of the positioning is time consuming.

The important question here is: how does the precision of sensor position measurements affect the reliability of the results generated for evaluating breakage probability? To answer that question we must find out how much the percentage loss in load-carrying capacity due to defects depends on the accuracy of sensor positions. For this comparison, we cut cross sections from various species of mature, decayed urban trees, and measured them tomographically using different sensor positioning methods. In addition, we compared results from estimated positions at the tree with caliper corrected versions.

NO #	POS [CM]	RAD± [CM]
1	462	3
2	23	-22
3	48	23
4	97	8
5	117	0
6	152	3
7	201	18
8	232	-17
9	253	12
10	302	4
11	346	6
12	368	-4
13	398	17
14	433	2

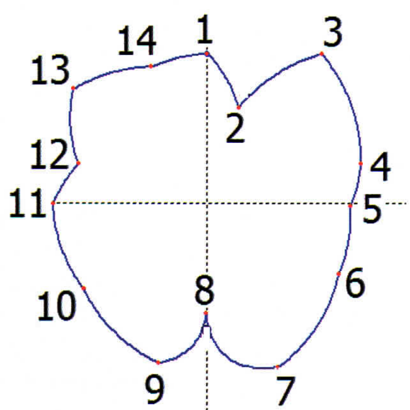

Figure 6. A typical approach to document sensor positions for sonic tomography is to record the location of each sensor on a circumferential tape measure (POS) and then the radial differences compared to an imaginary circle (RAD±). Some experts are using a plastic expandable circle covering the whole cross-section. Then, all sensors that do not touch the outer circle, get a negative radius difference. Recording these numbers usually takes a few minutes.

[cm]	1	2	3	4	5
1		38	?	?	?
2			14	36	?
3				?	?
4					?

Figure 7. In this table of the tomographic software, the first row and first column show the numbers of the sensors at the cross-section. In the white cells, caliper measured distances between the sensors can be put in. The software shows in colors for each sensor if there are sufficient distances measured: green indicates enough data points, the yellow marked sensors need some more measurements to other sensors, for the red marked sensors there is yet no distance to any other sensor defined. For each sensor, usually, 2 to 3 distances to other sensors have to be measured in order to provide sufficient data for a triangulation and determination of the precise position of the whole set of sensors at the tree. This usually takes several minutes.

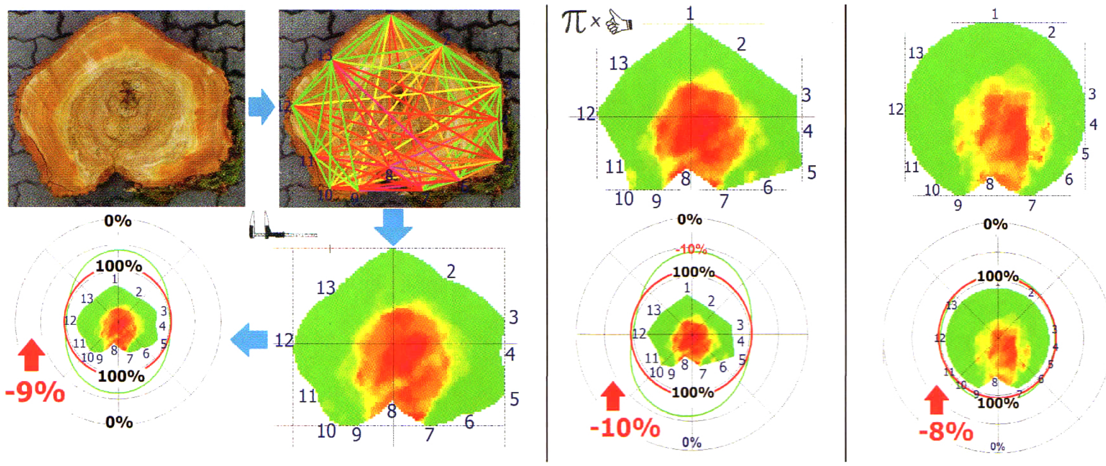

Figure 8. Precise sensor positions (Δ≤1cm) lead to a loss in section modulus and thus load-carrying-capacity of this defective cross-section of ~9% (left). Rounding sensor positions and radius differences to 5cm units (Δ≤5cm) results in ~10% (middle). Ignoring radius differences for all except one sensor, thus assuming a practically circular cross-section (right), leads to -8% estimated loss in load-carrying-capacity. In this example, maximum sensor position exactness, thus does not lead to a significantly different final result as compared to the quick and simple approaches.

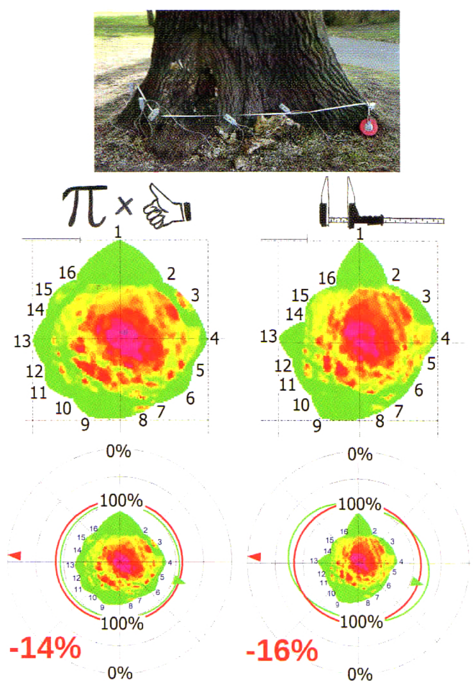

Figure 9. At this oak (Quercus petraea), a tree-risk expert, who was not yet experienced in sonic tomography, first recorded the positions of the sensors using a measuring tape (left) and guessing radius differences. Then, the sensor positions were determined precisely by using a caliper (right). Although the two cross-sections look different, the final and most important result of the assessment (=relative loss in load carrying capacity) did not vary significantly by increasing the accuracy of the sensor positions. In terms of a risk evaluation, there is not much of a difference between 14 and 16% loss in cross-sectional load-carrying-capacity.

RESULTS, SUMMARY AND CONCLUSIONS

A typical example of the numerous trunk sections we measured is shown in Figure 8. It clearly shows the change in the relative loss in load carrying capacity due to defects varies from 9% to 8 or 10% when sensor position accuracy is increased from ±10 cm (±4 inches), to ±5 cm (±2 inches), and then finally to ±1 cm (±0.4 inches). At the standing tree (**Fig. 9**), the step from estimating the sensor positions by using a tape measure with a corresponding accuracy of approximately ±5 cm (±2 inches) to using a caliper changed the loss in load carrying capacity from 14 to 16%.

This means that increasing the accuracy of sensor positions from estimations with approximately ±10cm (±4"), to ±5cm (±2") and then finally to ±1cm (±0.4") by using a caliper instead of a tape measure, did not significantly change the final and most important result of the sonic tomography (relative loss in cross-sectional load-carrying capacity due to defects). This confirms that the internal mathematical algorithm of the tested device (Arbotom®) delivers robust results and is not strongly dependent on sensor position accuracy. Thus, for Arbotom®, using a tape measure and estimating radial differences is usually sufficient. Other brands of sonic tomography devices may require using a caliper to assess precise sensor positions to obtain reliable tomography results.

Frank Rinn, Ph.D, Physicist and court-registered tree expert, Heidelberg, Germany (frank.rinn@rinntech.com)

References

Bertholf, L.D. 1965. Use of elementary stress wave theory for prediction of dynamic strain in wood. Washington State University Extension Bulletin 291, Pullman, WA.
Brandt, M. 1987. Anwendung der Ultraschall-Prüftechnik zur Stammfäulediagnose an stehenden Fichten. Diplomarbeit. Forstwissenschaftliche Fakultät, Universität Freiburg.
Crampin, S. 1984. An introduction to wave propagation in anisotropic media. Geophysical Journal International 76(1):17-28.
Fournier, A., Montuno, D. Y. 1984: "Triangulating simple polygons and equivalent problems", ACM Transactions on Graphics, 3 2): 153-174.
International Society of Arboriculture 2011: Best management practices: Tree risk assessment. Champaign, IL/USA, 81 pp.
Pellerin, R.F., De Groot, R.C., Esenther, G.R. 1985: Nondestructive stress wave measurements of decay and termite attack in experimental wood units. Proc Nondestructive Testing of Wood Symposium, Pullman, USA.
Rinn, F. 1999: Device for investigation materials. US-Patent US6813948; international Patent PCT/DE00/01467 (1999.05.11).
Rinn, Frank 2011: Basic Aspects of Mechanical Stability of Tree Cross-Sections. Arborist News, Feb. 2011, pp. 52-54.
Rinn, F. 2013: Shell-wall thickness and breaking safety of mature trees. Western Arborist, Spring 2013, pp. 40-44.
Rinn, Frank 2014: Central Basics of Sonic Tree Tomography. Journal of the Society of Commercial Arborists (SCA-Today), Dec 2014, Vol. 19, No. 4, pp. 8-10.
Rinn, F. 2015: Central defects in sonic tomography. Western Arborist, Spring 2015: 38-41.
Rinn, F. 2016: Intact-decay-transitions in profiles of density-calibratable resistance drilling devices using long thin needles. Arboricultural Journal. Volume 38, Issue #4, pp. 204-217.
Rinn, F. 2017: Key result of sonic tree tomography. Western Arborist, Fall 2017: 43-47.