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Short communication

Accuracy and Reproducibility of Acoustic Tomography Significantly Increase with Precision of Sensor Position

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Abstract
Acoustic tomograms are widely used in tree risk assessment. They should be accurate, repeatable and comparable between consecutive measurements. Previous work has failed to address the effects of different approaches to record sensor positions, operators and models of tomograph on the resulting tomograms.
In this study, three operators used the two most common sonic tomograph models to measure seven cross-sections of Norway spruce trees, which were felled after the measurement. We evaluated the effects of model, operator, and different approaches to measure sensor positions on the quality of the tomograms.
The largest source of error was the position of sensors, affecting estimated stress wave velocity, the shape of the tomogram, and the size of the defect.
To produce accurate and repeatable tomograms of trees with complex shapes, it is essential to measure the sensor positions precisely.

Keywords
Acoustic tomography; *Picea abies*; repeatability; reproducibility

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Contents

1. Introduction

Acoustic tomography is widely used in risk assessment in urban forestry, and in research in forest ecology and pathology.

Acoustic tomographs measure the time of flight of signals excited by hammer blows, and recorded by sensors fixed to the wood around the stem. From the time and distance data measured at the tree, the apparent stress wave velocity is calculated, assuming a straight path of the stress waves, because their true path is unknown.

When a stem cross-section contains decay, cavities, cracks, or included bark, time of flight of stress waves across the stem increases, because the stress waves must travel around the obstacle.

The result of sonic tomography is a map of apparent absolute or relative stress wave velocity, which will reveal areas of sound wood, if they can be traversed by stress waves on a straight path from one sensor to another.

Previous studies have shown the accuracy of the method, and how it depends on the number of sensors (Gilbert and Smiley, 2004; Li et al., 2012; Liang et al., 2008; Lin et al., 2011; Martins et al., 2013; Rabe et al., 2004; Rust, 2000; Wang et al., 2007, 2009).

Because stress wave velocity is calculated from the time of flight (measured by the sensors), and the distance between those sensors (measured by the operator), it seems essential to measure the distance between sensors exactly, since any error in distance will inevitably cause an equivalent error in velocity (Arciniegas et al., 2015). Often, quantitative mechanical evaluations of the tomogram in terms of the section modulus or its resistance to bending are part of a risk assessment. They will, however, suffer from errors in sensor positions, areas which are omitted because they are outside the polygon of sensors, and areas outside of the stem but within the polygon of sensors. Because the contribution of any part of the cross-section to the second moment of area increases with the square of its distance to the neutral axis of the stem, even apparently small inaccuracies in the measurement of the sensor positions and hence stem cross-section may result in significant errors in these calculations.

However, measuring all distances precisely can be time-consuming. The different products on the market today provide different solutions to this problem. Despite the critical importance of this part of sonic tomography, no research has been found investigating the effects of these approaches on the quality of the resulting tomograms.

Results of sonic tomography must be reproducible, especially for controversial trees, which might be assessed by different consultants for opposing clients.

When trees are deemed safe by a consultant, the report will often advise to make follow-up measurements after a period of some years. In these cases, it will be important that consultants can distinguish between effects of measurement uncertainty and a progression of decay.

So far, this issue of reproducibility has not been addressed in the scientific literature.

We compared the results of the two most common tomographs, which were applied by up to three different operators on the same trees.

This study evaluates the effects of the two most widely used approaches to account for the form of the stem cross-section on the accuracy of the tomograms. In addition, the differences between repeated measurements with the same or a different model of tomograph will be addressed.

This investigation will help risk assessors to make informed choices between the available methods. It will allow them to evaluate differences between tomograms made by different operators at different times. Knowing how different elements of the process contribute to uncertainty and reproducibility of tomograms will help consultants to produce better tomograms.

2. Methods and material

2.1 Trees

Tomograms were collected approximately at breast-height of five mature Norway spruce trees (*Picea abies*) with signs of butt rot, growing in a forest stand close to Heidelberg, Germany. In two of these trees, two additional measurements were made close to ground-level. After data collection, trees were felled and the cross-sections photographed. The cross-sections had diameters between 46 cm and 110 cm (median 77 cm).

2.2 Tomography

Data were provided by two court certified expert witnesses and one arborist. Devices were operated according to their manuals and training received by the manufacturers.

A total of 32 tomograms was collected from 7 different stem cross-sections. Three of these cross-sections were measured by three operators, three by two operators, and the remaining cross-section by one operator only. Each combination of cross-section and operator was measured with both devices, resulting in 16 paired measurements. Sensor positions were measured once for every combination of cross-section and device, resulting in 7 paired measurements.

The devices were an Arbotom (Rinntech, Heidelberg, Germany) and a Picus (argus electronic, Rostock, Germany). For the Arbotom, sensor positions are recorded as their position on the circumference of the tree, measured to the nearest 5 cm with a measuring tape. Adjustments can be made for their estimated divergence from a notional circle. For the Picus, an electronic caliper is used to triangulate sensor positions.

2.3 Image analysis

Tomograms and photos of the cross-sections were analyzed with ImageJ (Schneider et al., 2012). Cavities and areas of discolored wood were measured as defects in the photos, as well as all areas pink, red or dark orange in Arbotom tomograms, and all areas blue, pink, and green in the Picus tomograms. The second moment of area was calculated for 20 equally spaced axes through the centroid of tomograms and photos. For further analyses we used the median of these samples. R (R Core Team, 2016) was used for statistical analyses.

3. Results

3.1 Tomograms

Figure 1 presents the seven stem cross-sections and their tomograms.

3.2 Accuracy of stem form and sensor distances

3.2.1 Sensor distances

Distances between sensors measured during tomographic data collection and measured on the cross-sections after felling the trees correlated closely (fig. 2). Variability was higher for the Arbotom ($R^2 = 0.74$) than for the Picus ($R^2 = 0.89$). The deviation from the true distance increased with decreasing circularity of the stem cross-section (fig. 3). A root mean square error (RMSE) of 0.3 m equals a mean absolute error of more than 0.5 m.

3.3 Time of flight

Time of flight measurements of the two devices were very similar (fig 4). On average, time of flight measured by the Arbotom was significantly higher, especially at higher distances.

3.4 Areas of defects in stem cross-sections and in tomograms

While the proportional area of the defect in the tomograms measured with the Picus correlated closely with the true proportion measured in the stem cross-section ($R^2 = 0.65$, fig. 5), there was no correlation in the Arbotom data ($R^2 = 0$). There was a highly significant difference between the results of the two devices, but not between the results of different operators.

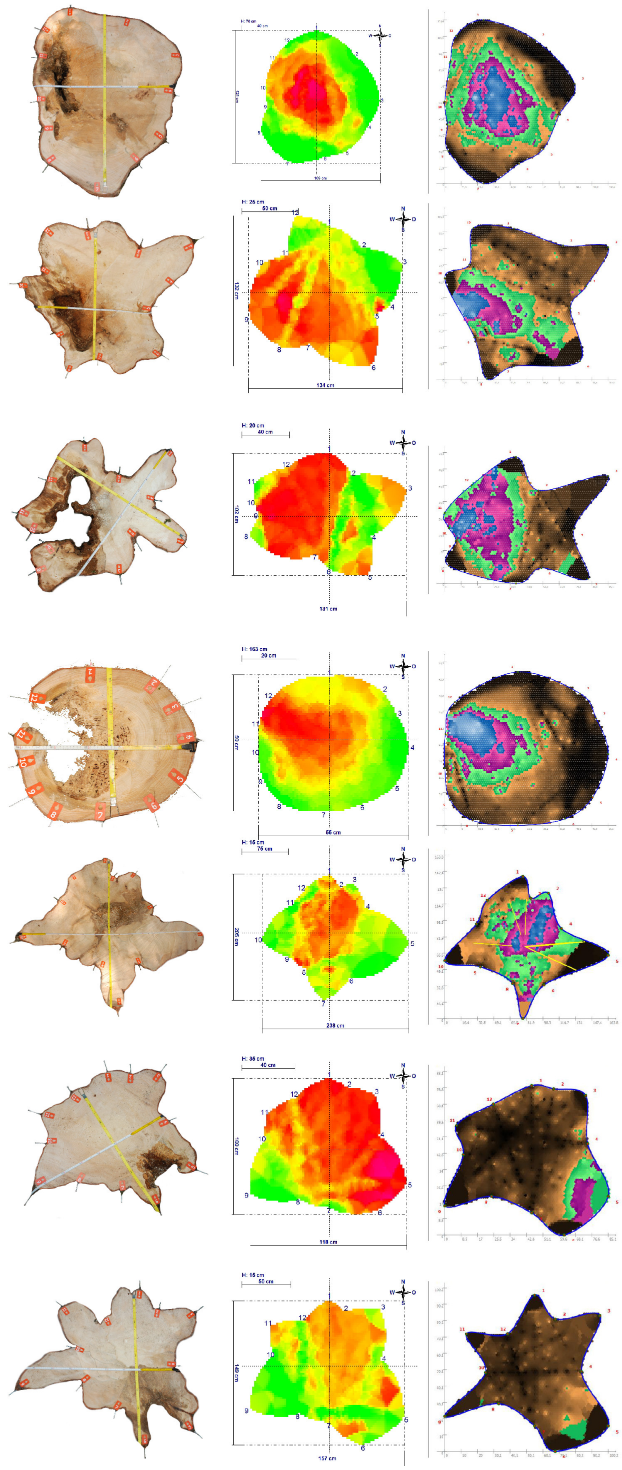

Figure 1. Cross-sections and tomograms. Middle row: Arbotom, bottom row: Picus.

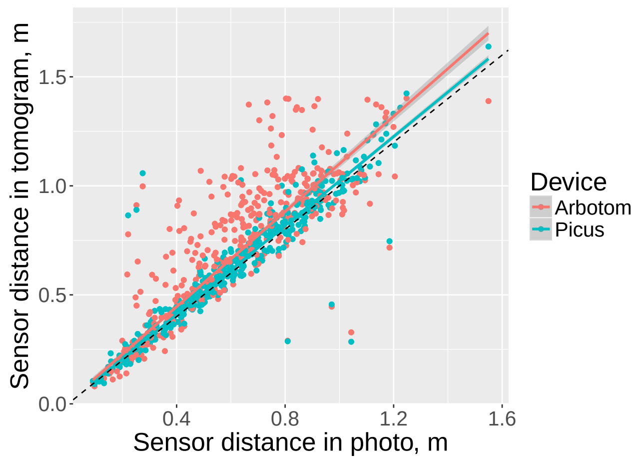

Figure 2. Correlation of true distances and distances measured by operator. Dashed line: 1:1.

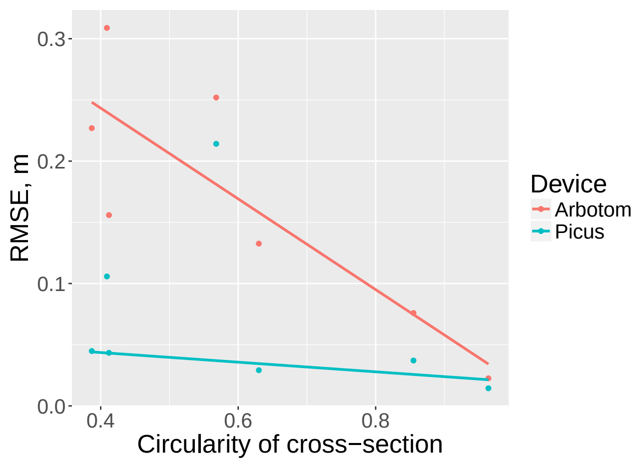

Figure 3. The error of distances (RMSE, root mean square error) increases with decreasing circularity of the section (a circularity of 1 describes a perfect circle).

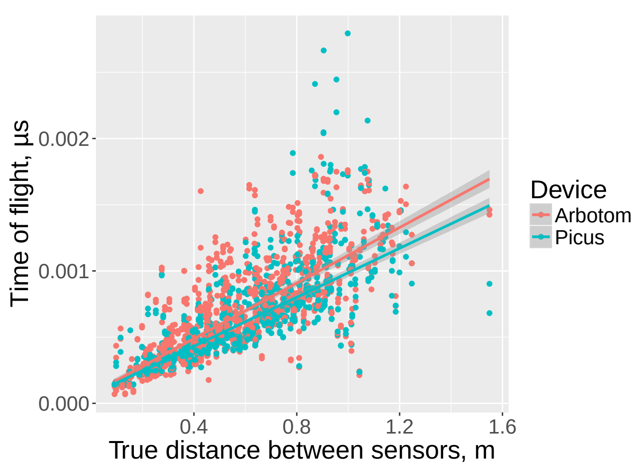

Figure 4. Comparison of time of flight measurements by device.

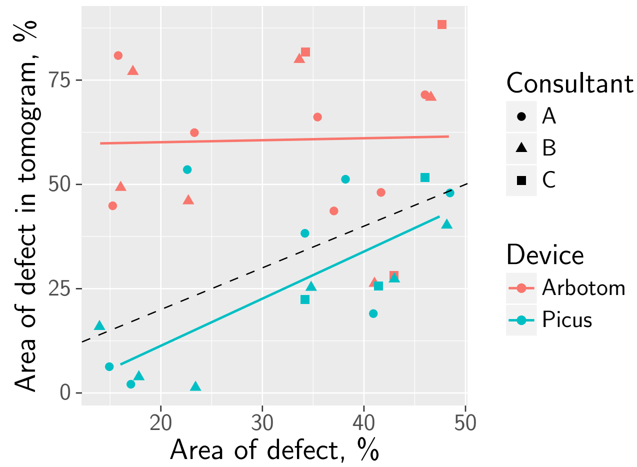

Figure 5. Proportional area of defects in the tomograms and photos. Dashed line: 1:1. Data jittered to reduce over-plotting.

3.4.1 Second moment of area

Figure 6 presents the medians of the second moment of area of the stem cross-sections. The different methods to record sensor positions results in very different moments.

3.5 Reproducibility

Figures 7 and 8 present six tomograms of the same stem cross-section. They are all similar, but differ in details. Differences between tomograms are smaller in the less complex cross-section.

4. Discussion

In risk assessment in urban forestry, reproducible results are very important, especially when controversial trees are assessed, or when it is likely, that decay will be monitored for many years. Although several major sources of variation were excluded in this experiment, up to three different operators produced similar, but not identical tomograms for each cross-section. In a real-world scenario, different consultants might choose different measurement levels at the tree, and/or different numbers and positions of sensors. A further source of variation will be the measurement of sensor positions. Thus, our results show, that it would be very likely, that different consultants would produce tomograms that look at least slightly different, even if they used the same model of tomograph. This should also be taken into consideration in the evaluation of follow-up measurements, which are often advised for trees with defects: differences between tomograms measured at different times might be caused either by a progression of decay, or just by differences in the measurement process.

Thus, when presenting a tomogram, measurement uncertainty and the accuracy of the devices should be addressed. Only then, differences can be evaluated correctly (Ramsey et al., 2006).

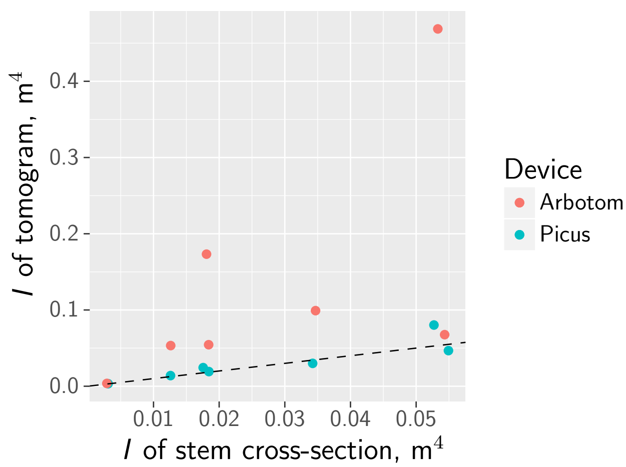

Figure 6. Medians of 20 equally spaced estimates of the second moment of area of the stem cross-sections. Dashed line: 1:1. Data jittered to reduce overplotting.

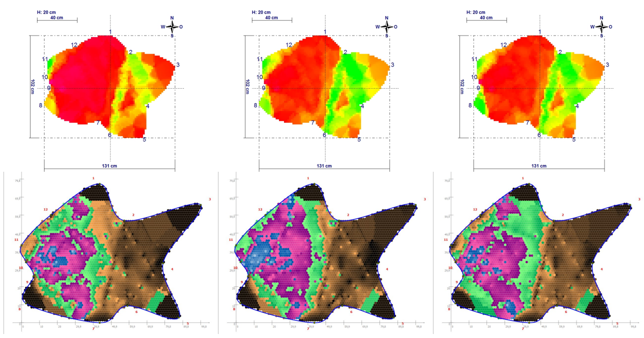

Figure 7. Tomograms of one tree, recorded by three different operators using the same nails. Top row: Arbotom, bottom row: Picus.

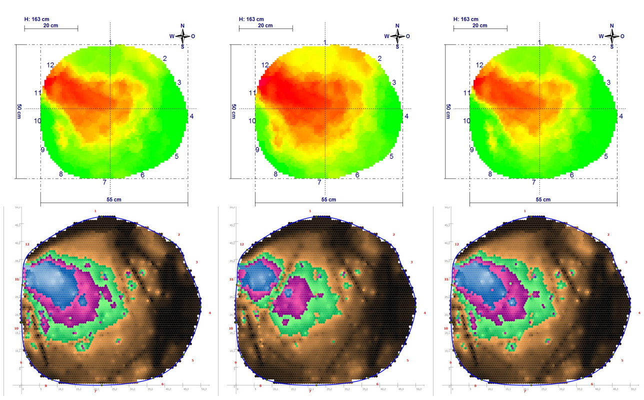

Figure 8. Tomograms of one tree, recorded by three different operators using the same nails. Top row: Arbotom, bottom row: Picus.

Sound velocity is calculated from time of flight and distance. While there were only marginal, though statistically significant, differences between the time of flight measured with both methods we compared, there were large differences in the distances. This resulted not only in large discrepancies in sound velocity and the tomograms calculated from these, but can also cause large errors in any mechanical analyses based on the tomograms. Both tomograph models we tested offer to evaluate the tomogram based on the section modulus. While this is problematic in itself, as it has to take the moduli of elasticity in tension and compression, as well as growth strains into account, all of which are generally unknown for a specific tree, all errors in the geometry will enter the calculation proportional to the third power of the distance to the neutral axis.

The deviations from the true shape of the trees were much larger when no triangulation was used. The operators were experienced and trained. It is therefore likely, that our results are representative for real-world applications. One reason for the large deviations might be, that while triangulation defines the shape of the tree uniquely, there exists an infinite number of shapes which all have the same circumference. A software solution based on the circumference of the cross-section can only guess the shape of the tree.

Although it can slow down the measurement of complex trees considerably, recording the sensor positions precisely is advised whenever the tomogram will be further evaluated based on residual wall thickness or section modulus, and if follow-up measurements are likely. In the latter case, the positions of sensors should be marked permanently to allow better comparisons between tomograms.

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