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X-ray imaging and computed tomography of conifer tree rings for climatological purposes

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Abstract. This paper presents images of wood structure for various measurement regimes of X-ray microtomography. This is done by obtaining tomographic slices (iSee, CTvox), averaging them with the help of a statistical script called Adobe Photoshop, converting the average images into multidimensional data sets, and then averaging the image profiles (OriginCalc) to finally obtain a two-dimensional array of dendrochronological series of tree-ring density. The results of measurements are checked by a weight method to confirm the reliability of the data processing algorithm. For dendrochronological measurements of the ring density, it is shown that, depending on the width, two modes can be used: 80-μm (for wide rings) and 30-μm (for narrow rings). A measurement mode of less than 10-μm is used to display the structure of the wood inside a ring. The results of XCT-density measurements performed with an 8-μm resolution are given to assess the daily changes in wood density during the growing season.

1. Introduction

To analyze the correlation between solar activity and wood growth, tree-ring characteristics were first used by A. E. Douglass [1] at the beginning of the 20th century. Other investigators, H. C. Frittsin [2] in particular, showed that environmental conditions greatly affect the tree growth, and tree rings were found to be an effective indicator of climatic changes.

The main dendrometric characteristics are the number and size (width) of tree rings, structure (pattern), and wood density [3]. To analyze these, visual, electro-optical and radiometric conventional techniques are used. X-ray radiation to measure the wood density was used by many researchers [3–5]. X-ray densitometric techniques are being successfully developed nowadays. The X-ray computed tomography (XCT) technique is one of them. X-ray tomographs used in medicine do not provide eligible spatial resolution that is required for tree-ring analysis [6]. Industrial X-ray tomographs have the highest resolution, but limit the sizes of wood cores [6, 7]. The problem can be successfully solved by using spiral XCT or synchrotron radiation tomographic microscopy techniques [8–10]. The techniques allow the analysis of large-sized wood cores with a resolution less than 100 μm.

The research aimed to develop a technique to assess the structure and density of tree rings of trunk wood using a high resolution scanning X-ray tomograph to solve dendroclimatology and biometeorology related problems. To test the efficiency of the developed technique, we compared the results obtained for the density of tree rings using a tomograph and measurements of the weight and size of individual rings or a group of rings.

2. Method

The XCT technique implies mathematical reconstruction of the inner three-dimensional structure of an object based on measurements of X-ray absorption under multiple irradiation of an object in different intersecting areas [11, 12]. The radiation absorption depends on the density of the substances that form the internal structure of an object. For visual and quantitative evaluation of the X-ray density *R*, the scale in Hounsfield Units (HU) is used to indicate the degree of radiation attenuation in the materials. The scale shows the ratio of radiation attenuation in the air to that in distilled water, the X-ray density of these being equal to 0 and 1000 HU, respectively, at standard pressure and temperature. The X-ray density is determined by the equation (1):

$$R = 1000\frac{\mu - \mu_{water}}{\mu_{water} - \mu_{air}}, \quad (1)$$

where μ, μ_{water} and μ_{air} are the linear attenuation coefficients for the material, water, and air under normal conditions, respectively. Negative R values indicate substances with less density as compared to water, and positive R values refer to those of higher density.

The X-ray density of the wood depends on both the type of wood and the physical state of the test wood sample, the main characteristics of which are temperature and humidity. To determine the physical density of wood based on XCT results obtained for test samples, calibration is performed using tomographic scanning of the reference wood sample with known density.

In dendroclimatology and biometeorology, dendrometric characteristics are determined through the analysis of samples in the form of cores or wood cuts of both fresh and dead trees. The selected samples were limited in maximum allowable size and the number of cores to prevent damage to a fresh tree. However, this limitation may reduce the representativeness of dendrometric characteristics.

A numerical experiment was carried out based on the extraction of a model 3D core from X-ray tomogram of a whole wood sample to eliminate this contradiction. The analysis of the virtual cores of different diameters indicated that statistically significant sample to measure dendrometric characteristics must contain not less than 7–8 cores with a diameter of 5 mm or 4 cores with a diameter of 12 mm. The obtained results are in good agreement with the data reported by Gjerdrum and Eikenes [13]. Mathematical processing of the scan data was performed using MATLAB R2017b (MathWorks Inc., USA) and ISee 1.11.1 (BAM Division 8.3, Germany), digital image processing was done in Adobe Photoshop CS6 13.0.1.3 Extended (Adobe Systems Inc. USA), and numerical analysis and data visualization were carried out using OriginPro 9.1 (OriginLab Corp., USA) and CTVox 3.3 (Bruker microCT, Belgium).

3. Instrument

We used two high-resolution X-ray tomographs TOLMI [10] and Orel-MT [14], where the test sample is scanned during its rotation. The tomographs have been developed in Tomsk Polytechnic University. TOLMI is the first design, and Orel-MT is an advanced version. The tomographs contain similar components and use the same operational parameters. However, Orel-MT has better contrast sensitivity and dynamic range, and it provides higher operational stability and shorter scanning time. X-ray sources are fine focus X-ray tubes with transmission targets. X-ray detectors are Gadox flat panels with TFT scintillators. The scan schemes use cone beam geometry. The main characteristics are given in Table 1, and the scheme of the tomographs and an interior view of the Orel-MT are shown in Figure 1.

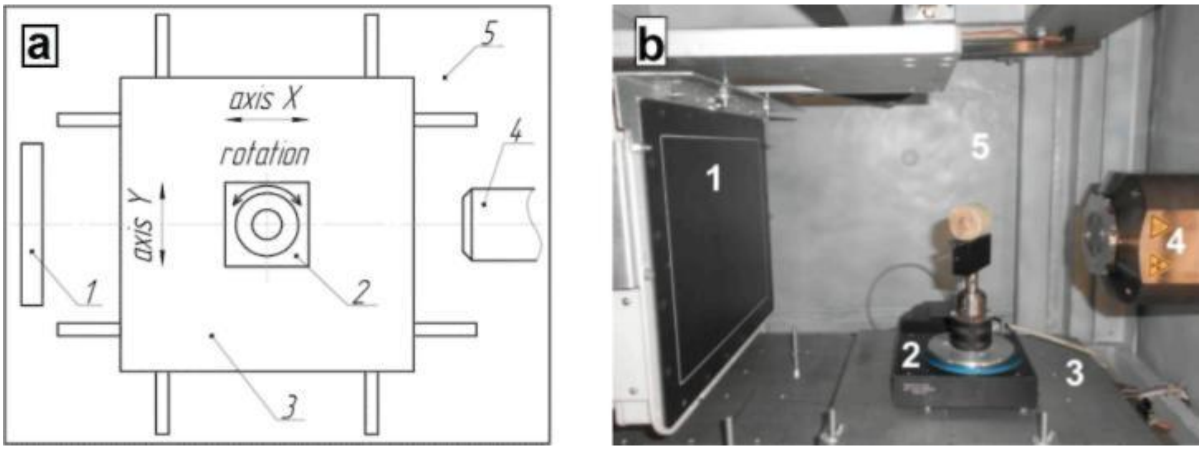

Figure 1. Scheme of the tomographs (a) and interior view of the Orel-MT (b): X-ray matrix detector (1); slewing table for examples (2); rail support (3); X-ray (tube) transmitter (4); protective housing (5).

Table 1. Main characteristics of X-ray tomographs.

Instrument	X-ray transmitter				X-ray detector			Geometrical characterics	
	Voltage (kV)	Current (μA)	Focal spot (μm)	Pitch (μm)	Active area (mm)	Active area (pixel)	Dynamic range (bit)	Magnifi-cation	Voxel size (μm)
TOLMI	40–140	100	40	96	98×96	1024×1000	12	×1.3–5	20–70
Orel-MT	20–160	1–500	1–20[a]	127	242×193	1900×1516	14	×1.3–25[b]	5–100[b]

[a] Focal spot size of the Orel-MT depends on current strength.
[b] The values of magnification and voxel size are limited by the precision of its mechanical parts.

4. Results

In our first dendrometric experiment, we analyzed dried wood samples (Figure 2) of 4–5-year pine (*Pinus sylvestris*), birch (*Betula pendula*), and Eurasian aspen (*Populus tremula*). The samples were taken in the forest near Tomsk and had diameters of 4–6 cm. The experiments were carried out with the tomograph TOLMI. The X-ray tube voltage varied from 60 to 100 kV, and the voxel size was 70 μm.

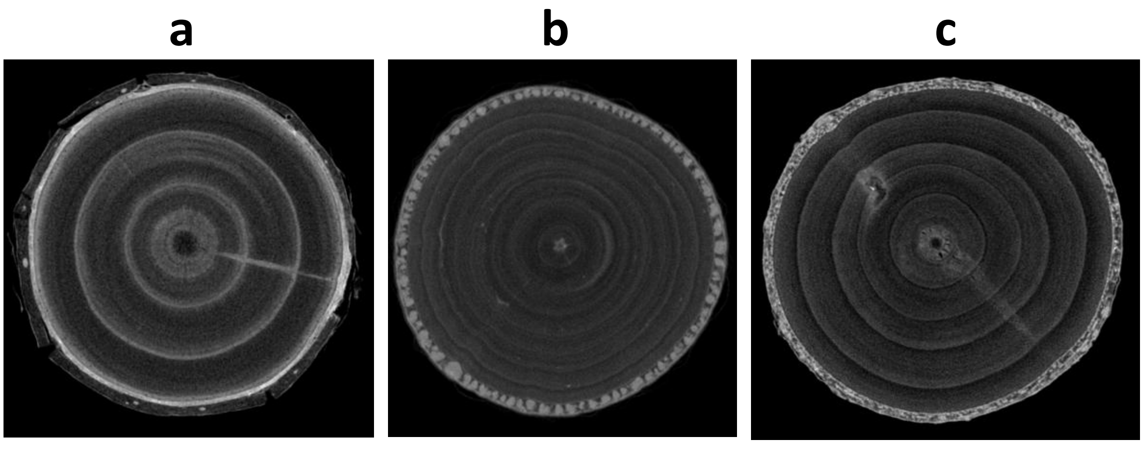

Figure 2. X-ray images of wood samples of pine (a), birch (b), and Eurasian aspen (c).

To achieve an optimal contrast for a scanned image, the tomograph operation modes were selected individually for each sample. Despite this, different physical density of wood samples affected the image contrast, which was different for different species of trees. The X-ray images of pine and aspen samples have better contrast than those of the birch sample. However, despite different contrast, the wood density profiles obtained from X-ray scanning show all seasonal and annual changes of tree rings.

Then we scanned 10×10×5- and 2×2×2-cm wood samples of 130-year Siberian pine grown in the Tomsk region. This experiment was carried out with the Orel-MT. The X-ray tube voltage was varied from 60 to 100 kV, and the current was about 50 μA. The scan resolution varied from ~7 to 90 μm. The results are presented in Figure 3.

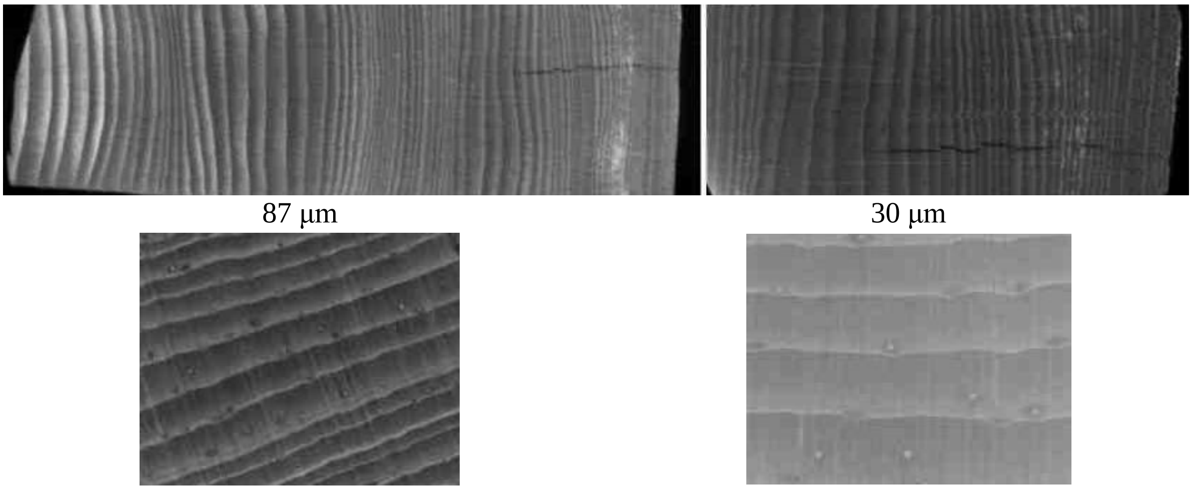

Figure 3. The X-ray images of wood samples of Siberian pine with a different scan resolution.

The quality of wood sample is essentially affected by its biophysical properties or state, which primarily implies wood moisture and gum resin (in coniferous trees). The freshly sawn wood sample had a natural moisture of 70–80 %. After drying it reached an equilibrium moisture content of 10–15 %. Measurements showed that a moisture saturated wood complicates the dendrological analysis of X-ray images. Therefore, wood samples should be dried before scanning. Another way is to use mathematical processing of X-ray images of freshly sawn samples.

5. Discussion

The measurement data obtained for tree ring density by the XCT technique was compared with the data obtained by the gravity (weight) technique to assess the measurement accuracy by the XCT technique. For this purpose, two wood samples in the form of 126×10×10 mm rectangular parallelepipeds were prepared from a radial segment of the Siberian pine cross cut dried to equilibrium moisture content. At first, a full-size scan of the samples was performed with 81-μm resolution. For higher resolution imaging (~30 μm), the samples were roughly divided into three parts and each part was scanned separately.

The tree-ring measuring station Lintab-5 [15] was used to determine the number of tree rings and their width in the samples. Then the samples were cut into layers with the width equal to that of tree rings. If the ring width was less than 1 mm, a separated layer included several rings. At the same time, the layer dimensions were constantly monitored using a caliper with an accuracy of 0.1 mm. The layers were weighed using the electronic balance Kern ABS-220-4 [16] with an accuracy of 0.1 mg. The wood density of tree rings was calculated for all layers. For the layers with several thin rings, the density of a single ring was assumed as an average value.

The X-ray density *R* was converted into physical density *D* by standard normalization using the equation (2):

$$D = \frac{(R - R_{\min})(D_{\max} - D_{\min})}{R_{\max} - R_{\min}} + D_{\min}, \quad (2)$$

where $R_{\min}$ and $R_{\max}$ are minimum and maximum X-ray densities; $D_{\min}$ and $D_{\max}$ are minimum and maximum wood densities.

The results of tree ring density measurement obtained by averaging over two wood samples using both techniques showed that the values over the first thirty years after the start of the yearly tree-ring formation almost coincide, for the growing period from 39 to 47 years the values show the inverse tendency, and after 50 years, the coincidence of the values is satisfactory. The correlation coefficient between two data series is 0.24 at a significance level of 0.05. The average relative difference between the values is less than 2 %, and the maximum difference does not exceed 28 %.

In our opinion, the observed differences are mainly due to the errors in manual division of samples into layers/rings during preparation for weighing. Tree rings of width less than 0.5 mm are quite difficult to divide. To do this, special high-precision equipment is required, but we did not have that. The complexity in division of very fine tree rings is a serious drawback of the weight technique if compared to the tomographic technique that is free of this shortcoming.

The possibility to analyze changes in the tree ring density using the XCT technique is shown in Figure 4, which presents the XCT image and density profile of the fresh (non-dried) pine wood obtained by XCT scanning with 10-μm spatial resolution. The X-ray image shows the layers of early (EW) and late (LW) wood in tree rings, as well as their fine structure that reflects the wood growth in different vegetation periods depending on changes in the environmental conditions, including climate and weather impact. The brightest areas in the image indicate moisture-saturated wood cavities and pores.

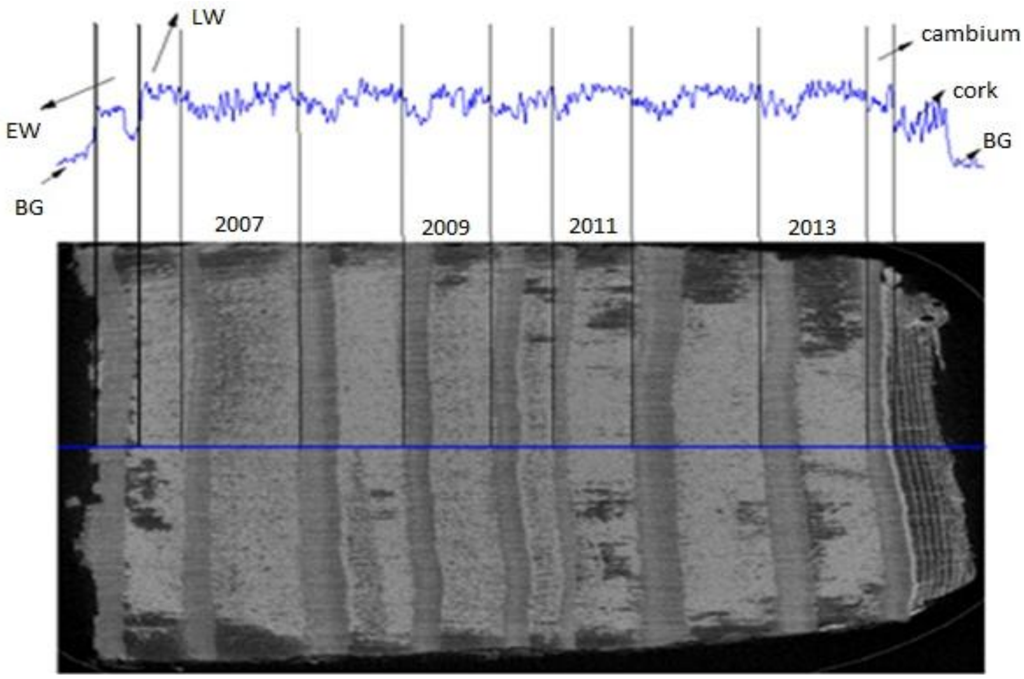

Figure 4. XCT image and density profile of the pine sample that illustrates a fine lamellar structure of wood density. Here BG is the background, i. e. the X-ray density of air.

6. Conclusions

The experiments performed using a high-resolution scanning X-ray tomograph to determine the structure and density of trunk wood tree rings showed that the XCT technique can be used to solve dendroclimatology and biometeorology problems. The XCT technique enables investigation of wood fine structure and precise measurement of the width and density of tree rings without destruction of wood samples. In addition, the technique allows elimination of subjective human errors to perform highly efficient dendrometric measurements and, thus, to preserve samples for further study or use.

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