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Verification technique for a photo-optical volume measuring system for stacks of timber logs

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Accurate volume measurement of stacked timber logs is essential for the timber industry. Photo-optical Automated Volume Measuring Systems (AVMS) offer efficient alternatives to manual methods but require verification to ensure reliability. This paper presents a simple, reliable, and easily implementable verification method for AVMS, based on measuring the wood stack front surface area. The proposed method utilizes reference models, calibrated using traceable working standards, to simulate timber log stacks with defined contours. This involves comparing the AVM's measured area to the reference model's area, enabling the determination of area measurement errors. The study investigates the selection of reference instruments, proposes a comprehensive AVMS verification procedure, and evaluates the method's metrological characteristics. Laboratory tests involving 110 AVMS units revealed a repeatability of 0.46% and a total uncertainty of approximately 1.1%. The method successfully identified shortcomings in commercially available AVMS, including non-compliance with manufacturer-declared errors and design imperfections related to camera limitations. The developed method can be used in industry, metrological supervision, and scientific research to ensure accurate and reliable measurements of wood stacks and the long-term reliability of AVMS. This study also highlights the need to further improve photo-optical measurement systems to increase their reliability and accuracy.

Keywords: Photo-optical Measuring Systems, Volume, Stacked Timber Logs, Verification, Standards Calibration, Conformity Assessment

Introduction

Accurate measurement of timber stacks is crucial for the timber industry, especially for financial transactions and logistical planning (Purfürst et al. 2023). Recent advancements in sensor and camera technology have led to the development of photo-optical measurement methods (Berglund 2014, Moskalik et al. 2022). Automated measurements significantly reduce the time and effort required (Borz et al. 2022). These systems typically capture images of timber stacks and use image-processing algorithms to determine dimensions, volume, and other relevant parameters (Matzku 2024). The software identifies the outer boundary of the timber stack in the image, defining the two-dimensional area of the stack's front surface. Advanced algorithms can provide more accurate and transparent measurements compared to manual methods, minimizing the risk of mistakes associated with manual calculations (Borz & Proto 2022, Xu et al. 2024). Detailed records of measurements and corresponding stack images enable the collection of valuable data for forest management and research (Cremer et al. 2021, Borz & Proto 2022). Despite their advantages, photo-optical systems still face certain challenges. For example, accurately measuring complex stack shapes can be challenging for some systems (Tomczak et al. 2024).

Adverse weather conditions such as rain, snow, or poor lighting can affect image quality and measurement accuracy (Berendt et al. 2021). Regular inspection of photo-optical AVMS can help prevent significant measurement errors by enabling timely maintenance or recalibration. Researchers have evaluated the reliability of these new methods (Pasztory et al. 2018), identified factors contributing to measurement deviations (Matzku 2024, Ucar et al. 2024), and compared systems from various manufacturers (Purfürst et al. 2023). However, little attention has been given to the verification procedures for such systems. Essential elements include: selecting reference standards and ensuring their traceability; implementing the principle of comparing two measuring instruments and assessing key metrological characteristics; and determining appropriate measurement conditions.

A conformity assessment process represents a commitment to safety, quality, and fair competition, benefiting manufacturers, regulators, and consumers (Mjakuškina & Lapina 2018). It evaluates whether a product meets the requirements of relevant legal acts, standards, and technical specifications (Castka et al. 2023). Conformity assessment is not merely a bureaucratic hurdle, as it offers significant advantages for all parties involved. For manufacturers, it provides a gateway to legal market access (Yadav et al. 2023). By demonstrating compliance, manufacturers can avoid fines and legal disputes, and they gain a competitive edge through increased customer confidence (Mattarozzi et al. 2023). The assess-

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ment process itself can be a valuable tool, helping manufacturers identify and rectify weaknesses in their production processes, which can lead to greater efficiency and cost reduction (Friederich & Lazarova-Molnar 2024). Regulatory bodies also benefit, as conformity assessment helps ensure that only safe and reliable products reach consumers. By identifying non-compliant products, regulators can take action against manufacturers who disregard regulations. Data gathered through conformity assessments inform the development and refinement of future regulations and standards (Demetzou & Rovilos 2023). Ultimately, conformity assessment provides a vital layer of assurance that the products consumers purchase are safe, function as intended, and meet the advertised quality.

Regular verification (if legally required) or calibration, along with routine maintenance, is necessary to ensure ongoing measurement accuracy and reliability. Conformity assessment procedures are carried out with traceability to national or international measurement standards (ILAC-P14: 09 2020). This means that the system's measurements must be compared to reference values. In practice, the measured dimensions are compared to known reference values to evaluate the system's accuracy. Conformity assessment procedures for photo-optical systems may use different terminology across national legal frameworks. In some countries, these systems are classified as legal metrology instruments, while in others they are considered under industrial metrology. In this paper, we refer to the conformity assessment procedure for these systems (when treated as objects of legal metrology) as verification, and we establish traceability to standards through calibration. The implementation of these procedures remains essentially similar in all cases (Winter 2012).

The objectives of this work are (i) to assess the key metrological characteristics in the verification of photo-optical measurement systems; (ii) to propose simple, reliable, and implementable solutions for verifying photo-optical systems used to measure the area of wood stacks, and to integrate them into a common geometric dimension traceability framework; this includes developing a verification methodology with a clear sequence of actions, selecting appropriate reference instruments and calibrating a reference "model", and quantitatively assessing the method's reliability; (iii) to evaluate a series of measuring instruments, determine the compliance of photo-optical measurement systems with their manufacturer-declared metrological characteristics, and identify shortcomings related to camera limitations and software operation.

Methods

Theoretical study

Photo-optical systems capture multiple images of a timber stack's front face. Software then stitches these images together to create a complete digital representation of the stack's face. The software identifies the outer boundary of the woodpile in the image, defining the two-dimensional area of the stack's face. These systems employ various algorithms to estimate the woodpile's volume based on the captured area.

Metrological characteristics of a photo-optical system

The key metrological characteristics of these systems are the area measurement error and the measurement range of the timber stack's front surface area. These parameters are directly related to the measurement process itself. Additional factors pertain to the algorithms used for volume calculation. The calculated total volume accounts for both the solid wood and the air spaces between the logs. A conversion factor *k* accounts for the difference between the volume of the stacked timber and the solid wood content. The ratio of solid wood to total stack volume can vary between ~50% and ~80%, depending on the type and shape of the wood (Witkowska & Jodlowski 2019).

The combined standard uncertainty of a volume estimation using such a system consists of three components: (i) uncertainty in the front surface area of the logs (the surface perpendicular to the log length); (ii) uncertainty in the length of the stacked logs; and (iii) uncertainty in the conversion factor. The standard uncertainty of the front surface area is equal to $u(A) = \pm \delta_A/\sqrt{3}$, where $\pm \delta_A$ is the maximum permissible area error of the system as declared by the manufacturer. Different wood species vary in shape, bark thickness, and straightness, all of which influence stacking characteristics. For instance, crooked logs create more air gaps than straight logs. Methods for determining the conversion factor *k* include using published data or tables of typical *k* values for different wood types and conditions (StateNews 2003), as well as employing image analysis techniques (in some advanced systems) to estimate the fill factor by analyzing the gaps between logs. The uncertainty associated with the conversion factor *k* is critical to accurate volume estimation of stacked timber (Tomczak et al. 2024). The standard uncertainty of *k* can be derived from its maximum error and can be calculated as $u(k) = \pm \delta_k/\sqrt{3}$. If the error of the conversion factor $\delta_k = \pm 0.05$ and the conversion factor ranges from 0.5 to 0.8, then the standard uncertainty of the conversion factor is equal to 4%-10%, depending on the type and shape of the wood. Typically, the accepted log length in practice is slightly greater than the average log length, with an extra allowance of 5-10 cm added (StateNews 2003). In this analysis, we assume there is no uncertainty in the length measurement, taking its uncertainty as zero ($u(l) = 0$).

The relative error of volume estimation with the photo-optical system is calculated using $k=\sqrt{3}$ for a rectangular distribution according to (eqn. 1):

$$\delta(V)=\sqrt{\delta_A^2+\delta_k^2} \qquad (1)$$

Based on the above considerations, the relative volume estimation error for a photo-optical system can range roughly from 3% to 10%, depending on the type and shape of the wood (Gajjar 2017, Matzku 2024, Tomczak et al. 2024, Xu et al. 2024). If the volume calculation algorithm does not use the conversion factor *k*, the volume estimation error depends only on the area measurement error.

Main elements of the verification procedure

As mentioned earlier, the final result calculated by photo-optical systems is a volume, obtained as the product of the measured area, the conversion factor, and the log length. For verification purposes, this volume can be effectively equated to the measured area by setting $k = 1$ and $L = 1$. These two factors are set to unity because they are not directly measured by the system but rather are predefined (by agreement or by image analysis results). Therefore, verification focuses on measuring the

Tab. 1 - Main elements of the verification procedure for log stack photo-optical systems.

Conformity assessment parameters	Front surface area *A* of logs
	Area measurement range
Standards selection	Identifying suitable reference standards
	Construction of log stack templates/models
	Calibration of log template area
Main stages of method implementation	Measurement of the area bounded by the contour of the stack template with a photo-optical system (selected different contour areas are measured at different distances
	It is assumed that the volume of a stacked log is calculated according to the formula: $V = A \cdot k \cdot L$, where *k* and *L* are 1 during verification
	Evaluation of the error of the template/model area and its comparison with the permissible error of AVMS: $\delta A \leq \delta A_{permissible}$

stack's end-face area as determined by the instrument. This same area is also measured using reference instruments, and the measurement error is calculated and compared to the manufacturer's permissible error specification.

Reference models with geometric dimensions near the instrument's specified minimum and maximum measurable areas are tested to cover the full measurement range of the photo-optical system. The system is considered compliant when the area measurement errors at both the minimum and maximum test areas remain within the acceptable error limits. Taking all of this into account, the main elements of the verification procedure are summarized in Tab. 1.

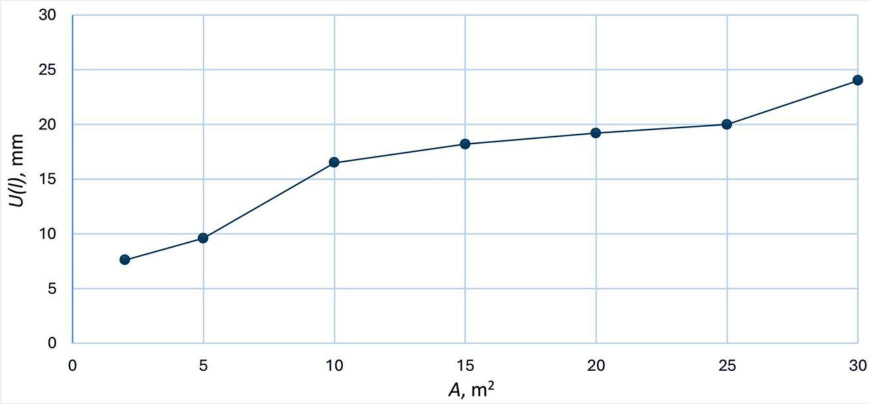

Fig. 1 - Dependence of the expanded uncertainty of length reference standards on the measured area.

Key considerations for reference instrument selection

When selecting a reference instrument for verification, several key factors must be considered to ensure accurate and reliable measurements. First, the reference instrument should be traceable to national or international standards and must have a valid calibration certificate from an accredited laboratory. Second, to minimize the impact of the reference instrument's uncertainty on the overall measurement uncertainty, the reference instrument's uncertainty should be at least three times smaller than the uncertainty (or maximum error) of the instrument being tested (OIML-G-19 2017). Thus, during the selection process, the standard's calibration uncertainty is directly compared to the photo-optical system's permissible error.

The reference model's area is calculated from measured lengths, so directly comparing the uncertainty of a length-measuring standard (*e.g.*, a laser distance meter) to the permissible area error of the AVMS is not straightforward. We therefore relate the reference instrument's calibration uncertainty to the uncertainties in the measured lengths that define the area. Appendix 1 (Supplementary material) details the theoretical derivation of the calibration criteria for standards, based on the relationship between length measurement uncertainty and the permissible area error for rectangular log stack models. For log stack AVMS, the relative error of the total log pile area δ_A is typically determined (Cremer et al. 2021, Tomczak et al. 2024).

The calibration technique utilizes two primary categories of measuring instruments. A ruler, tape measure, or laser meter is employed to measure the edges of the log stack model. The length of the reference measure L_R must be greater than or equal to the largest side of the model contour L. Furthermore, the expanded uncertainty $U(L_R)$ of these measuring instruments must be less than or equal to the value determined by the following (eqn. 2):

$$U(L_R) \leq \frac{\delta A_{permissible} \cdot a \cdot b}{100\% \cdot 3 \cdot (a+b)} \qquad (2)$$

where $\delta A_{permissible}$ is the relative permissible error of AVMS, and a and b are the lengths of the sides of the rectangular model (Fig. 1), expressed in meters.

Log stack templates, or models, serve as reference standards for verifying the AVMS. The reference area of the model contour A_{mod} ranges from 2 to 20 m². The expanded uncertainty of the model area $U(A_{mod})$ must be less than or equal to one-third of the relative permissible error of AVMS: $U(A_{mod}) \leq \delta A_{permissible} / 3$. The uncertainties and errors are given in either absolute or relative terms, aligning with the technical specifications provided by photo-optical system manufacturers. When selecting standards according to the aforementioned criteria, it is crucial to verify that the target error ratio is achieved after calibrating the model's contour area. This area is calibrated during the AVMS verification process.

Proposed method for photo-optical system verification

This section outlines the process for verifying AVMS used to measure the volume of timber log stacks. The operating principle of an AVMS relies on a combination of image analysis and mathematical calculation. Because the system's software analyzes an image to determine the area within a defined contour, verification compares the measured area of that contour with a corresponding reference value.

A specially constructed reference model provides the reference value by simulating a timber log stack with a known contour area. The area of this model can be accurately measured using manual length measurement instruments. The model must be calibrated under the same environmental conditions as the AVMS under test.

For accurate measurements, the model should be mounted on a flat, vertical plane parallel to the plane of the AVMS's imaging system. The reference models should represent different points across the device's measurement range in terms of log stack area. To ensure and assess reproducibility, the model areas are measured at various distances from the device. We propose using two reference models with distinct contour shapes. Their areas should be close to the minimum and maximum area limits that the device under test can measure. For example, as illustrated in Fig. 2, one model could have an area of approximately 4-8 m² and the other around 10-14 m², representing different stack shapes at the low and high ends of the instrument's range.

Measurement of the area bounded by the contour of the model with a reference measuring instrument

The edges of the constructed rectangular or polygonal models must be identified as shown in Fig. 2. These edges are highlighted and designated as *a*, *b*, *c*, *d*, and *f*. The lengths of the edges L_a, L_b, L_c, L_d, and L_f are measured using a reference instrument (*e.g.*, a tape or laser distance meter).

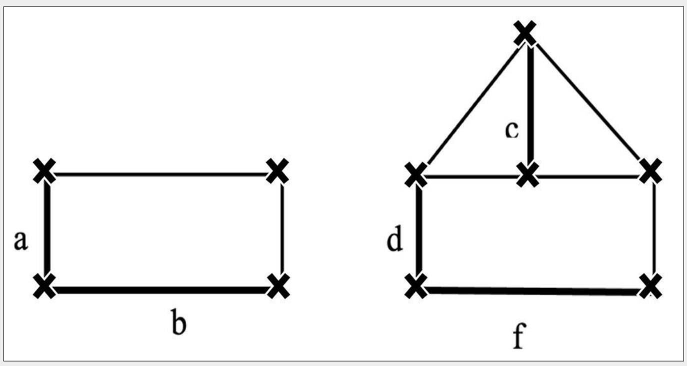

Fig. 2 - Examples of formed rectangular and polygonal models.

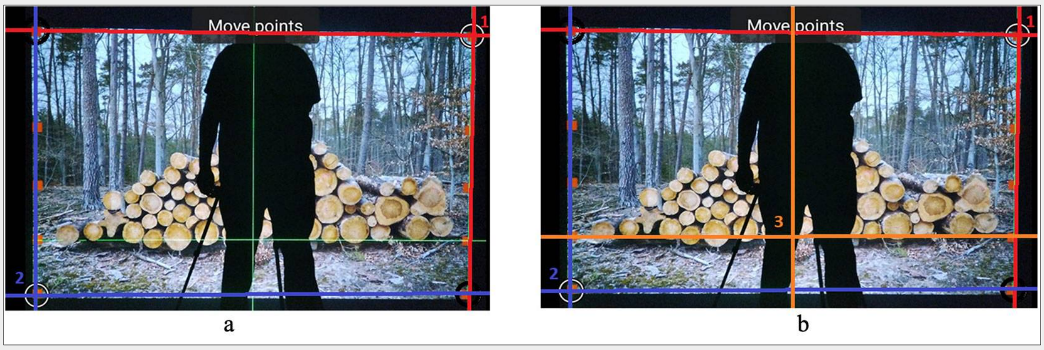

Fig. 3 - Establishing the reference perimeter using laser levels.

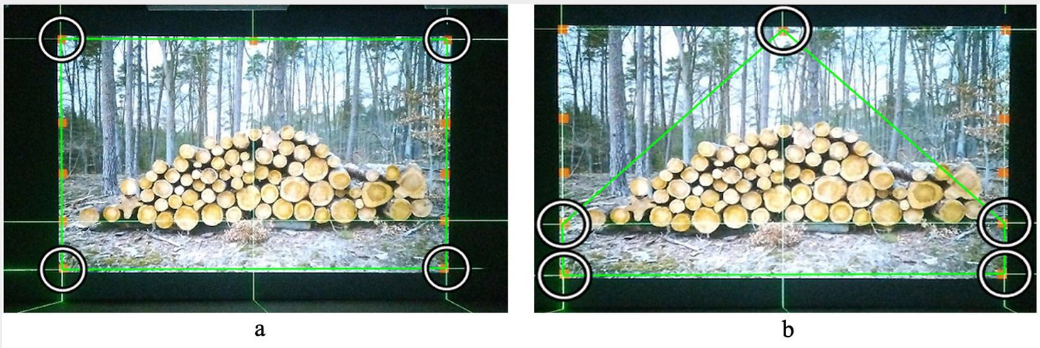

Fig. 4 - The reference points for the rectangular and polygonal area.

Lengths are recorded in meters to three decimal places. Each edge is measured five times, and the average length is calculated according to the following formula (eqn. 3):

$$\bar{L}_x = \frac{1}{5}\sum_{i=1}^{5}\left(L_{xi} + \Delta_s\right) \quad (3)$$

where $\bar{L}_x$ is the average edge length in meters, x is an index denoting the edge *a, b, c, d*, or *f* of the model's contour, i is an index representing the measurement number, i = 1, … , 5; and Δ_s is the calibration error of the reference measuring instrument, obtained from its calibration certificate.

The areas of the models are calculated using the following equations (eqn. 4, eqn. 5):

$$A_{rect} = \bar{L}_a \cdot \bar{L}_b \quad (4)$$

$$A_{poly} = \bar{L}_f \cdot \left(\bar{L}_d + \frac{\bar{L}_c}{2}\right) \quad (5)$$

The area uncertainty was calculated in accordance with the ISO/OIML principles of uncertainty propagation. The total standard measurement uncertainty for each model contour edge length is calculated as detailed in Appendix 2 (Supplementary material). The expanded uncertainty of each model's area is then obtained using the following equation (eqn. 6):

$$U(A_j) = \frac{2u_c(A_j)}{A_j} \cdot 100\,\% \quad (6)$$

where j is an index denoting the shape of the model, either rectangular or polygonal.

The expanded uncertainties of the areas bounded by the contours of the formed models must meet the criteria $U(A_j) \le \delta A_{permissible}/3$, where $\delta A_{permissible}$ is the relative maximum permissible error of the AVMS. If this condition is not met for a given model, the model's contour needs to be adjusted (*e.g.*, use a smaller or simpler shape) and the uncertainty recalculated. The model contours should be refined until the expanded uncertainty of their area measurements meets the specified criterion.

Application of the proposed method

For the verification procedure of the log stack AVMS, a simulated log stack template (reference model) was constructed and used (Fig. 3). This model was calibrated under the same environmental conditions as the AVMS and constructed on a smooth, vertical plane. Laser levels ensured accurate alignment of the model's edges. For rectangular reference models, two horizontal and one vertical laser level were used, providing leveling accuracy of about ±1 mm to ±1.5 mm per 10 m in both horizontal and vertical directions.

For the initial system test, area measurements were performed at a randomly chosen distance from the photographed plane. This verified the system's ability to account for varying distances. The system must correctly recognize the captured image as the outline of a pile of logs. To verify the AVMS ability to calculate volume, we set the corresponding values of log length L and the density factor k. For each combination of L and k, the expected volume V is calculated using the formula $V = A \cdot k \cdot L$.

A photograph of an actual log stack was projected onto the same vertical plane as the reference model to activate the measurement system's edge-detection algorithm (*i.e.*, to ensure the system "sees" a realistic log arrangement within the reference contour). A reference outline was then established using three laser levels. Two laser levels defined a large outer rectangle: the intersection of their vertical and horizontal laser lines was aligned with the predetermined reference corner points (lower-left and upper-right) of the desired outline, as shown in Fig. 3a. This created the perimeter of the outer rectangular reference area. The third laser level created an internal horizontal reference line. Its vertical and horizontal beams were aligned approximately with the midpoint of the projected log stack's top horizontal edge, at roughly 25%-40% of the total height from the bottom of the projection (Fig. 3b).

The required geometric dimensions of the reference outline were then measured using a laser distance meter, using the intersections of the laser lines as reference points. From these measurements, the areas of both the rectangular and polygonal reference shapes were calculated. Fig. 4a shows the reference points for the rectangular area, and Fig. 4b shows the reference points for the polygonal area.

The areas of the reference model contours were also measured using a reference laser distance meter with 1 mm resolution, a systematic calibration error of -0.03 mm, and an expanded uncertainty of 0.8 mm. During the measurement of each contour edge, the readings were corrected by subtracting the reference instrument's calibration error, applying the -(-0.03 mm) = +0.03 mm correction where appropriate. The pile width (m), pile height (m), and total area (m^2) as determined by the AVMS were recorded on a tablet computer (see Fig. 5 for an example of the recorded results display).

Two operators carried out the tests on separate batches of AVMS devices. The first batch contained 48 photo-optical systems, and the second batch contained 62, for a total of 110 devices tested. The devices under test are photo-optical volume measurement systems for timber log stacks, each employing at least two stereo-cameras. According to the manufacturer, the device measures the cross-sectional area of a log stack by detecting its contour (using an algorithm). Then it calculates the volume based on the log length and a filling (density) coefficient. The manufacturer-declared metrological specification is an area measurement error of ±3%. The device has certain operating limitations, including a valid working distance from the stack (min. 3 m, max. 8 m), a minimum ambient light requirement (> 2 lux), and a tolerance for camera alignment (the camera's image plane must be within ±5° of parallel to the log stack end-face or truck trailer).

For all verification measurements, the AVMS was set to its "Contour" operating mode, with the log length L = 1 m and the stack density coefficient k = 1 (100%). The system allows the detected pile contour to be adjusted *via* user-selected boundary points (Fig. 4). The captured image of the model with the outlined contour, along with any manual contour adjustments, was saved in the measurement results report for each test.

To evaluate the errors of each device under test, the area enclosed by the contour detected by the AVMS was compared to the corresponding area measured by the reference method. Measurements with the device under test were performed for both reference model shapes at two distances: approximately 3.3 m and approximately 7.1 m from the model's vertical plane. Two measurements were taken in each case for each distance and model shape. The calculated relative deviation of the area for each model at different distances is equal to: $\delta A_{system} = 100 \cdot (A_{system} - A_{model}) / A_{system}$, where A_{system} is the area value measured by the AVMS, and A_{model} is the reference area value of the model contour calculated by eqn. 4 and eqn. 5. The relative deviation δA_{system} of each measurement must not exceed the permissible error declared $\delta A_{permissible}$ by the manufacturer.

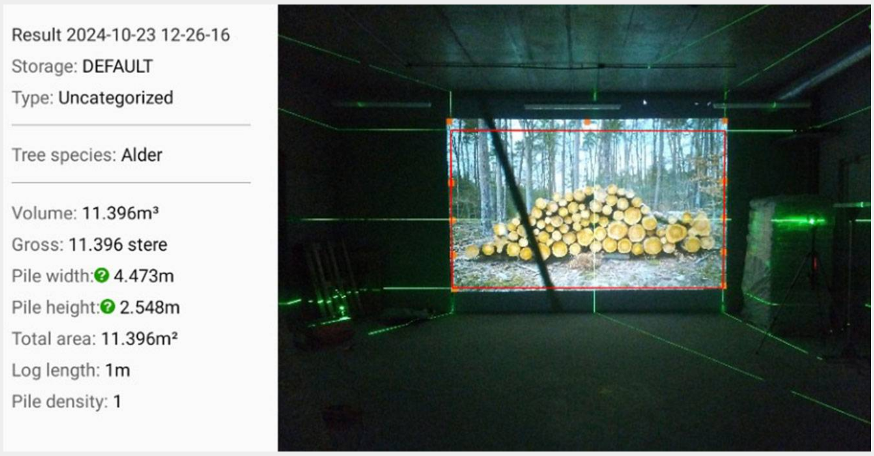

Fig. 5 - Display of the recorded results on the tablet.

Tab. 2 - Summary of uncertainty budget for contour area measurement with a working standard. (σ): standard uncertainty; (σ_c): combined standard uncertainty; (W): sensitivity coefficient; ($\sigma_c \cdot W$): component of the combined standard uncertainty, evaluated for its contribution.

Sources of uncertainty		Value (m)	σ (m)	σ_c (m)	W (m)		$\sigma_c \cdot W$ (m^2)	
					A_{rect}	A_{poly}	A_{rect}	A_{poly}
Calibration of a standard ($\Delta_s \pm U_s$)		-0.00003	0.00041	-	-	-	-	-
Resolution (Δ_r)		0.001	0.00041	-	-	-	-	-
Contour edge measurements	$\bar{a}$	2.612	0.00032	0.00059	4.3776	-	0.00258	-
	$\bar{b}$	4.3776	0.0006	0.00078	2.612	-	0.00204	-
	$\bar{c}$	2.0626	0.00075	0.0009	-	2.1888	-	0.00197
	$\bar{d}$	0.5494	0.00051	0.00072	-	4.3776	-	0.00315
	$\bar{f}$	4.3776	0.0006	0.00078	-	1.5807	-	0.00123
Standard combined uncertainties for measuring areas : $u_c(A_{rect})$ = 0.00330 m^2, $u_c(A_{poly})$ = 0.00247 m^2								
The areas bounded by the contours of the models: A_{rect_mod} = 11.434 m^2, A_{poly_mod}= 6.920 m^2								
The expanded uncertainty of the bounded area: $U(A_{rect})$= 0.058 %, $U(A_{poly})$= 0.071 %								

Results and discussion

The verification process consists of two main parts: (i) calibrating (measuring) the simulated reference model's area; (ii) comparing the device-under-test's results to the reference measurements. Before examining device performance, we also consider the calibration results for the reference model areas. Tab. 2 presents the measured areas of the reference model contours and their uncertainties.

Our results show that conventional working standards with a scale division of about 1 mm can be effectively used to measure a simulated reference model's dimensions. When using such common measuring tools, it was not necessary to apply any additional correction factors from the reference instrument's calibration certificate to the raw measurements, as the small systematic error of the standard was negligible at this scale. The correlation between opposite edge measurements of the rectangular models was insignificant, so covariance terms between edges could be neglected in the uncertainty evaluation for area calibration.

For each AVMS device under test (from both batches), the relative area deviation δ was calculated for both reference models at both test distances. Fig. 6 summarizes the combined results for all 110 tests. Out of 110 photo-optical systems, 12% (13 systems) did not meet the manufacturer's declared ±3% permissible error for area measurement. Overall, the results are approximately normally distributed, indicating that the measurement errors are predominantly random, with no strong systematic bias across devices. However, the distribution of area deviations for the first batch of devices is skewed toward negative values, indicating that those systems tended to underestimate the area. In contrast, the distribution for the second batch is skewed toward positive values, indicating that those devices tended to overestimate the area. We suspect these between-batch biases stem from slight differences in camera alignment or calibration among the devices, especially noticeable when photographs were taken from farther away.

To evaluate the overall reliability of the verification method, we assessed not only individual device errors but also the method's repeatability and reproducibility. The standard deviation of repeated area measurements (reflecting short-term repeatability) varied with area size and camera distance. For reference model areas between about 6 m^2 and 12 m^2, the standard deviation of the AVMS's area readings ranged from roughly 0.2% to 0.3%. The method's reproducibility, evaluated by varying conditions such as distance and operator and examining variation in results, was approximately 0.46%.

The overall uncertainty of the verification method includes the uncertainty in determining the reference model's area, the

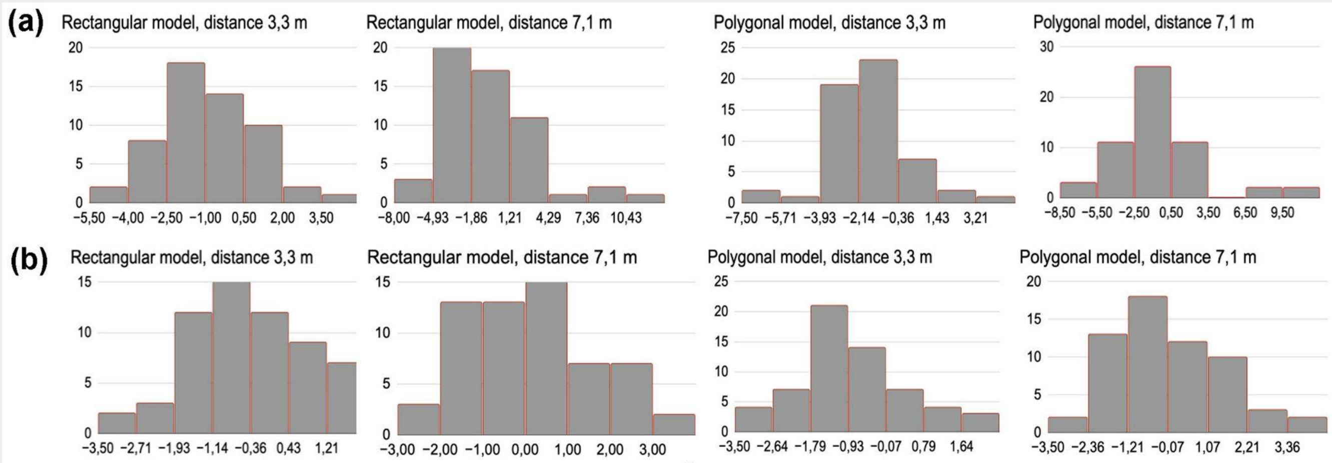

Fig. 6 - Summarized results of area evaluation errors for all samples of both batches (a and b): relative area error on the *x*-axis, number of samples on the *y*-axis.

method's repeatability, and its reproducibility. Taking all these components into account, the total expanded uncertainty of the verification method is approximately 1.1%. The relative expanded uncertainty can be expressed by the following (eqn. 7):

$$U(A_{meth}) = 2\sqrt{u_{mod}^2 + u_{repeat}^2 + u_{reprod}^2} \quad (7)$$

where u_{mod} is the standard uncertainty of contour area measurement with a working standard, u_{repeat} is the uncertainty due to repeatability based on a calculation of a standard deviation of area measurement obtained from multiple measurements, and u_{reprod} is the standard deviation of multiple repeatability test results where the conditions of measurement have been changed. To calculate the overall uncertainty, we used the maximum observed values of these components as a conservative estimate.

This verification method reliably ensures the performance of photo-optical systems when manufacturers declare an allowable area error of 3% or greater for timber stack end-face measurements. This holds true provided that a 1:3 uncertainty ratio between the reference standard and the device under test is maintained during reference instrument selection (Tomczak et al. 2024).

Conclusions

This study presents the key aspects of conformity assessment procedures for photo-optical volume measurement systems used for log stacks. It describes a practical methodology, validated under laboratory conditions, applied to AVMS in the context of metrological supervision (verification). The proposed procedure ensures that AVMS comply with legal requirements by guaranteeing traceability to internationally recognized units.

A simple, reliable, and easy-to-implement verification method for photo-optical AVMS for measuring the area of wood stacks has been developed and tested. The method is based on reference models whose areas are measured using working standards with fine scale divisions (0.5-1 mm). The procedure covers various aspects of AVMS verification, including identifying key performance characteristics, selecting suitable reference instruments, simulating and calibrating reference models, evaluating measurement characteristics, and processing the results.

We comprehensively evaluated the metrological performance of the method. Its reproducibility is high (on the order of <1%), and the total uncertainty is about 1.1% (relative, expanded). Using this method, we identified several shortcomings in current commercially available AVMS, including instances of non-compliance with the manufacturers' declared error specifications and some design limitations, particularly related to camera alignment and imaging. Nonetheless, the verification method allows us to test and confirm the accuracy of existing AVMS (with manufacturer-declared area errors of 3% or more).

The findings of this study are relevant to developing new standards and guidelines in this field. International organizations such as ISO and IEC continue to develop standards to meet the needs of emerging technologies. Harmonizing standards across regions reduces duplication of effort and facilitates global trade by ensuring products are evaluated using consistent criteria.

Overall, the proposed verification technique is a valuable tool for ensuring the accuracy and reliability of AVMS in the timber industry. Its application can improve measurement accuracy, help detect potential problems in AVMS, and contribute to more efficient and fair timber trade. Future research and development should focus on further mitigating camera-related limitations and improving image-processing algorithms in photo-optical measurement systems to enhance AVMS accuracy and reliability. It is worth noting that this verification method enables performance testing in laboratory conditions rather than in the field, significantly reducing the economic burden on AVMS operators and contributing to environmental goals, *e.g.*, by avoiding unnecessary travel or machine operation, thereby reducing emissions.

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Supplementary Material

Appendix 1 - Theoretical derivation of calibration characteristics for length standards.

Link: Meskuotiene_4869@suppl001.pdf

Appendix 2 - Measurement of the total standard uncertainty of the area bounded by the contour of the model.

Link: Meskuotiene_4869@suppl002.pdf