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Potential of Measure App in Estimating Log Biometrics: A Comparison with Conventional Log Measurement

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Abstract: Wood measurement is an important process in the wood supply chain, which requires advanced solutions to cope with the current challenges. Several general-utility measurement options have become available by the developments in LiDAR or similar-capability sensors and Augmented Reality. This study tests the accuracy of the Measure App developed by Apple, running by integration into Augmented Reality and LiDAR technologies, in estimating the main biometrics of the logs. In a first experiment (E1), an iPhone 12 Pro Max running the Measure App was used to measure the diameter at one end and the length of 267 spruce logs by a free-eye measurement approach, then reference data was obtained by taking conventional measurements on the same logs. In a second experiment (E2), an iPhone 13 Pro Max equipped with the same features was used to measure the diameter at one end and the length of 200 spruce logs by a marking-guided approach, and the reference data was obtained similar to E1. The data were compared by a Bland and Altman analysis which was complemented by the estimation of the mean absolute error (MAE), root mean squared error (RMSE) and normalized root mean square error (NRMSE). In E1, nearly 86% of phone-based log diameter measurements were within ±1 cm compared to the reference data, of which 37% represented a perfect match. Of the phone-based log length measurements, 94% were within ±5 cm compared to the reference data, of which approximately 22% represented a perfect match. MAE, RMSE, and NRMSE of the log diameter and length were of 0.68, 0.96, and 0.02 cm, and of 1.81, 2.55, and 0.10 cm, respectively. Results from E2 were better, with 95% of the phone-based log diameter agreeing within ±1 cm, of which 44% represented a perfect match. As well, 99% of the phone-based length measurements were within ±5 cm, of which approximately 27% were a perfect match. MAE, RMSE, and NRMSE of the log diameter and length were of 0.65, 0.92, and 0.03 cm, and 1.46, 1.93, and 0.04 cm, respectively. The results indicated a high potential of replacing the conventional measurements for non-piled logs of ca. 3 m in length, but the applicability of phone-based measurement could be readily extended to log-end diameter measurement of the piled wood. Further studies could check if the accuracy of measurements would be enhanced by larger samples and if the approach has good replicability. Finding a balance between capability and measurement accuracy by extending the study to longer log lengths, different species and operating conditions would be important to characterize the technical limitations of the tested method.

Keywords: wood; diameter; length; close-range sensing; LiDAR; Augmented Reality; comparison; accuracy; effectiveness; potential

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1. Introduction

Measurement and grading are important activities in the wood value chain because they provide essential quantitative and qualitative information for transactions. The wood is commonly delivered to the industry as roundwood [1–5], for which a volume estimation is required to document the delivered quantity and to form the basis for payment. Ideally, a single measurement done in the forest could act as a transaction interface between the suppliers and customers [6–8] and would ease the effort and resources spent in these activities. However, in complex wood supply chains (e.g., [9]) characterized by a low integration of technology, as well as for reasons such as removing public suspicion, preventing illegal logging, enabling traceability, and building trust, supplementary checks of the wood may be required, particularly by third parties such as the public authorities. In Romania, for instance, a typical example is that of taking custody over the wood by a carrier, which requires detailed measurement, grading, and reporting in a wood tracking system at the landing, before making the delivery [10] and, in case of suspicion, additional checks may be in question within the wood value chain. There are many other examples in practice and science in which wood measurement is required. In felling areas or at the landings, a pre-grading of the wood which includes measurement, is required for optimal bucking by motor-manual means [1]. In forestry-related scientific applications of time and motion study wood measurement is a prerequisite for estimating the amount of production and characterizing the productivity in relation to operational factors [11–16].

There are many methods that can be used to estimate the volume of individual logs. Depending on the procedures used to measure the required parameters, and in particular, on the type of contact between the measuring instrument and the log under measurement, they can be fairly categorized into two groups: direct and remotely-sensed measurements. Direct measurement methods include the estimation of wood volume by hydrostatics [17], gravimetry [17], and water displacement [17–19], as well as conventionally by a tape and a caliper. Measurement by hydrostatics, gravimetry, and water displacement is typically constrained to scientific applications and it is limited by the size of the logs and infrastructure needed [17]. Estimating the volume of a log by conventional methods is commonly used in practice and requires biometric information about the length and diameter(s) of the log. Depending on the concept used to estimate the volume, log diameter may be measured at both ends or at the middle, then the log is typically assimilated to a cylinder when making the mathematical computations to estimate its volume [17]. Measuring wood biometrics such as the diameter, height, or volume by remote sensing includes the use of photogrammetric [20,21], time of flight (ToF) [21,22], and Light Detection and Ranging (LiDAR) [23] based methods, many of which still share some limitations, namely the need to post-process the data and the high data acquisition costs incurred by the instruments and software used. Although phone-based compact solutions integrating remote sensing technologies were developed specifically to provide real- or near-real time estimates on some biometrics of standing trees [24] and logs [22], in our knowledge, solutions dedicated to replace measuring tapes and calipers for length and diameter measurement of the logs were not developed, meaning that in many geographical areas this activity still needs to rely on manual, direct-contact measurements, which are typically done in challenging environments such as in the felling areas, or in conditions which constrain the access to logs, such as those characterizing the wood piled at the landing.

The developments in mobile phone technology by the integration of common-use measuring applications based solely on the performance of phone cameras or integrating also the capabilities of LiDAR technology and Augmented Reality (AR) environments has opened new doors for potential applications in forestry. Apple's Measure app [25], for instance, could be a potential alternative to measuring log biometrics (diameter and length), which could provide the benefits of excluding rather uncomfortable to carry equipment such as the forest tapes and calipers while including their capabilities into a single device. Currently, the Measure app uses AR technology and it was first released for free without the support of LiDAR sensors, which became an integrant part of the iPhone devices starting with the 12th version, namely the iPhone 12 Pro and iPhone 12 Pro Max; in turn, the integration of LiDAR sensors resulted in improved accuracy and quicker measurement capabilities as claimed by the producing company. The application enables making several measurements, and copying and pasting the results into external applications for further use [25], making it suitable for saving the results of measurement. Still, its suitability in providing accurate results in log measurement was not tested. In this regard, only one study was found on the topic of using the Measure app for estimating the breast height diameter of the trees [26], but the device used has not been equipped with a LiDAR sensor.

The goal of this study was to compare the measurements taken on the diameter and length of coniferous logs by the use of the Measure app supported by a LiDAR sensor and AR (hereafter phone measurement, PM) with those taken by conventional means (hereafter conventional measurements, CM), namely a tape and a caliper, in two experiments. A first experiment was set up to emulate the real-world measurement conditions by taking the PM by a free-eye approach, meaning that no guiding marks were placed on the logs to support picking up the starting and ending points of a given PM. In a second experiment, PM were guided by marks placed on the logs at the points at which the CM on diameter and length were taken. Two objectives were pursued by this study. The first was to check the agreement between PM and CM in both experiments having as a reference the CM data and the second was to check the accuracy of PM in both experiments, having as a reference the CM data.

2. Materials and Methods

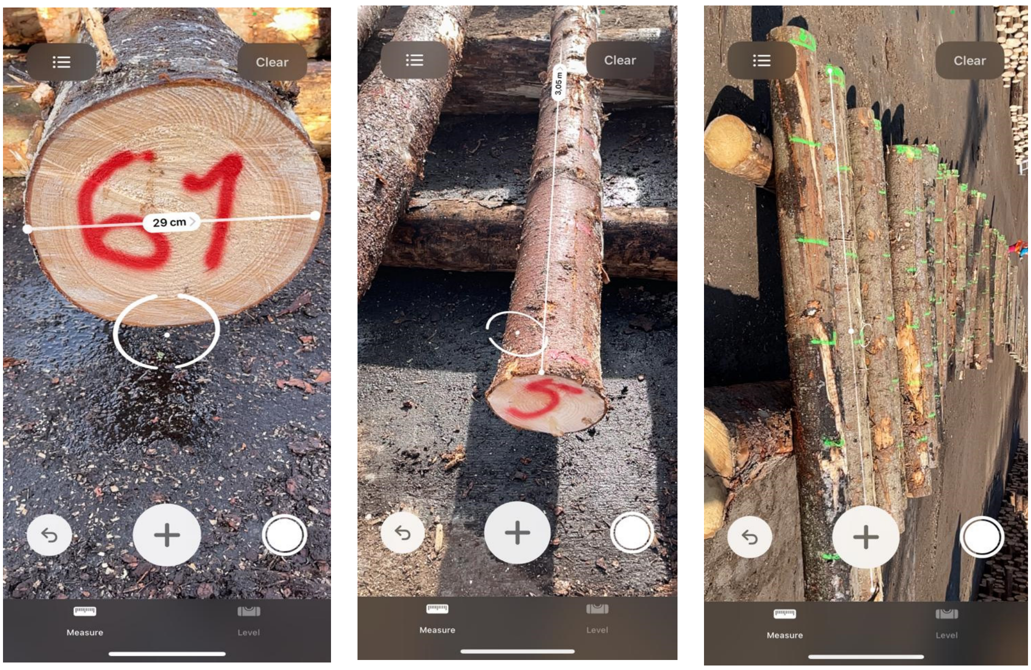
2.1. Study Location and Data Collection

Data used in this study were collected in the sawmilling facility of the HS Timber Productions Reci S.R.L., which is located near the village of Reci, Covasna, Romania at the coordinates of 45°51′01″ N–25°56′52″ E. The company processes coniferous logs, mostly of Norway spruce (*Picea abies*, L. (Karst)), which is one of the dominant coniferous species in Romania [27]. Typically, the logs are delivered at the factory gate in lengths of 3 to 4 m. In the period used to collect the data, the sky was mostly clear and the weather was relatively cold.

Two experiments (hereafter E1 and E2) were set up to collect the data for this study. In E1, the main approach of phone-based measurements was that of emulating the real-world measurement conditions in which no guiding marks are available on the logs, therefore the measurement needs to rely on the experience of the operator in setting the starting and ending points to measure the diameters and the lengths of the logs. For this experiment, the field data collection was done on the 14, 15, and 17 February 2022, by considering a total number of 267 logs.

To facilitate log measurement by using both, a measurement tape and a forest caliper (CM) and the phone-based Measure app (PM), the logs measured in each of the three days were placed on transversal logs and spaced at ca. 60 cm apart (Figure 1). Then, an identification number (hereafter ID) was painted on each log taken into the study (Figure 1) and the logs were marked at half-meter intervals starting from the painted end with the aim of preventing accidental measurement errors and supporting data collection. Where/When was the case, the additional length which was less than half a meter was painted on the opposite end. Conventional measurement (CM) was done to the nearest centimeter by a field researcher using a forestry caliper and a measurement tape. For comparison purposes, one diameter was measured for each log at the end painted with the identification number (hereafter Dman, cm), by approaching the log with the caliper placed perpendicularly on the log axis, in a vertical plane, with arms oriented downwards. The length (hereafter Lman, cm) was measured by a forestry tape on the upper part of each log. Data on log ID, Dman, and Lman was noted in a field book. To estimate the volume of each log by conventional measurement and formulae, the diameter at the middle (cm) and at the second end (cm) of each log were measured by the same procedures and noted accordingly in the field book. As the conventional measurement progressed, the Measure app installed on an iPhone 12 Pro Max smart phone device developed by Apple was used to measure the diameter at the end painted with the log ID (hereafter Dmeas, cm) and the length of the log (hereafter Lmeas, cm). The measurements were taken by a free-eye approach, meaning that no marking signs were placed on the logs to delimitate the starting and ending points of the measurement. The functionalities of the application used are given in Figure 2 by some examples. Dmeas was taken in a direction that was as close as possible to the parallel to the ground, by a line that followed the diameter of the log, and Lmeas was taken between the middle points of the log's ends located at the upper part of each log.

Figure 1. An example of log placement to facilitate measurements. Note: numbers painted in red stand for the identification numbers of the logs.



(**a**) (**b**) (**c**)

Figure 2. Examples of diameter and length measurements by the Measure app of iPhone in the first experiment (E1): (**a**) an example of using the Measure app and AR for diameter measurement; (**b**) an example of using the Measure app and AR for length measurement; (**c**) perspective in AR over a group of logs and a measurement on log length.

Diameters (Dmeas) were measured from a distance of up to 0.5 m and the lengths (Lmeas) were measured by walking along the log at a slow walking speed. Initial and final measurement points of the Dmeas and Lmeas were taken from a close perspective to the log. For Dmeas, these measurement points were taken as close as possible to the log ends on its diameter (over the bark) while for Lmeas they were taken as close as possible to the log ends. Although the AR environment enables adjustments of the measurements, for simplicity and for keeping the procedure as close as possible to that eventually used in practice, such adjustments were not done over the measurements. Once the measurements over Dmeas and Lmeas were done, their results were noted in the field book.

In E2, the main approach of the experiment was to guide the researcher in placing the initial and final PM points for both diameter and length measurements. The data of E2 was collected in the same location between the 11 and 15 April 2022 and accounted for a number of 200 logs. The procedures used to conventionally measure the log diameters and lengths were complemented by marking with dots (ca. 1 cm in diameter, Figure 3) the points at which the caliper arms were tangent to the log end when measuring the diameters, as well as the end points located at the top of the log, which were used as starting and ending points to measure its length by the tape.

(**a**) (**b**)

Figure 3. Examples of diameter measurements by the Measure app of iPhone in the second experiment (E2): (**a**) an example of log with marks placed; (**b**) an example of measurement over the log's end diameter: 1—starting and ending points of measurement, 2—dot marked as the starting point of measurement for log length.

In this experiment, measurements on the mid and opposite diameters of the log were disregarded. However, the rest of the experimental design used for conventional measurement was kept the same and it included the activities of placing marks at a 0.5 m interval and painting the excess length on the opposite end when it was less than 0.5 m. Also, the platform used for PM was an iPhone 13 Pro Max. In both experiments and for both methods, the measurements were taken at the nearest centimeter.

2.2. Data Processing and Statistical Analysis

In experiment 1 (E1) the data collected by the two measurement methods were manually transferred into a Microsoft Excel® spreadsheet equipped with a Real Statistics add-in, where further processing steps were taken to estimate the volume of each log by the Huber's (hereafter VH, m^3) and Smalian's (hereafter VS, m^3) formulae. The statistical steps used to compare the data consisted of running a normality check by the means of a Shapiro-Wilk test, developing the main descriptive statistics for the variables taken into study (Dman, Lman, Dmeas, Lmeas, VH, and VS) followed by a graphical comparison of the volume estimates, and a comparison of the two measurement methods by the means of Bland and Altman's method [28] applied to the diameters (Dmeas vs. Dman) and lengths (Lmeas vs.

Lman) and having as a reference the values collected by the conventional method (CM). Where relevant, a confidence level of 95% ($\alpha < 0.05$) was assumed.

The method developed by Bland and Altman is typically used to compare two measurements of the same variable in terms of agreement assuming that each measurement is affected by errors [29]. As such, the method may be used when one attempts to test or introduce a new measurement method, procedure, or instrument, being applicable when the acceptable limits of agreement can be defined a priori [28,29]. At its core, the method is based on a plot that compares the means of each pair of measurements against the differences between them in a space characterized by the mean of differences (bias) and a 95% prediction interval called the limits of agreement (upper and lower limits of agreement) [28]. Measurement agreement between the methods is typically achieved when the values of differences are clustered around the bias within two standard deviations of their mean [28,29]. The method assumes that the values of differences between the compared pairs are normally distributed, although failing a normality test is seen to be not as serious as in other statistical contexts [28], and requires checking and applying various methods to deal with heteroskedastic data [29].

The procedures used to run the analysis consisted in calculating the differences between paired measurements of diameters (hereafter ΔD) and lengths (hereafter ΔL), computing the bias as the mean of differences, setting the limits of agreement within two standard deviations of differences, checking for normality in differences and plotting the data. In addition to the development and visual analysis of the Bland and Altman plots, testing for homoskedasticity was done by plotting the squared residuals of the CM (Dman, Lman) data against the predicted values of PM data (Dmeas, Lmeas), followed by a Breusch-Pagan test for homoskedasticity [30,31]. In addition to Bland and Altman plots, graphs showing the absolute frequencies of differences were developed to characterize their frequency and magnitude. Also, the data collected by CM and PM were pairwise compared in graphs showing the equality lines [28] and regression through the origin (RTO) which fitted the PM as response and CM as explanatory variables.

Finally, error metrics such as the mean absolute error (MAE), root mean square error (RMSE) and the normalized root mean squared error (NRMSE) were estimated having as a reference the datasets collected by CM, with the aim of quantifying the differences between the two methods. MAE is defined as the ratio of the sum of absolute differences between the reference and measured data to the number of observations in a given sample, RMSE takes the square root of the ratio of squared differences between the reference and measured data to the number of observations in a given sample and the NRMSE is the ratio of RMSE to the data range in a given sample. These error metrics are commonly used to compare among paired values of the same variable as they stand for the average difference rather than average error when no set of estimates is known to be the most reliable [32]. As such, in this study, they were used to point out the differences between the two measurement methods. Excluding the volume estimation and comparison, processing and statistical analysis of the data from E2 followed the same procedural steps.

3. Results

3.1. Experiment 1 (E1): Free-Eye Measurement

3.1.1. Descriptive Statistics of E1

Table A1 shows the results of the normality check which was carried out by the means of the Shapiro–Wilk test. As shown, none of the variables taken into study followed a normal distribution. The main descriptive statistics of the log volume estimates by Huber's (HV) and Smalian's (VS) formulae are given in Figure 4b in the form of a boxplot. On average, the values estimated by the two formulae were close (VH = 0.132 and VS = 0.135 m^3), but the data range was wider in the case of VS (0.655 m^3) as compared to VH (0.501 m^3). This came largely from the maximum values which were higher in the case of VS (0.688 m^3) as compared to VH (0.531 m^3).

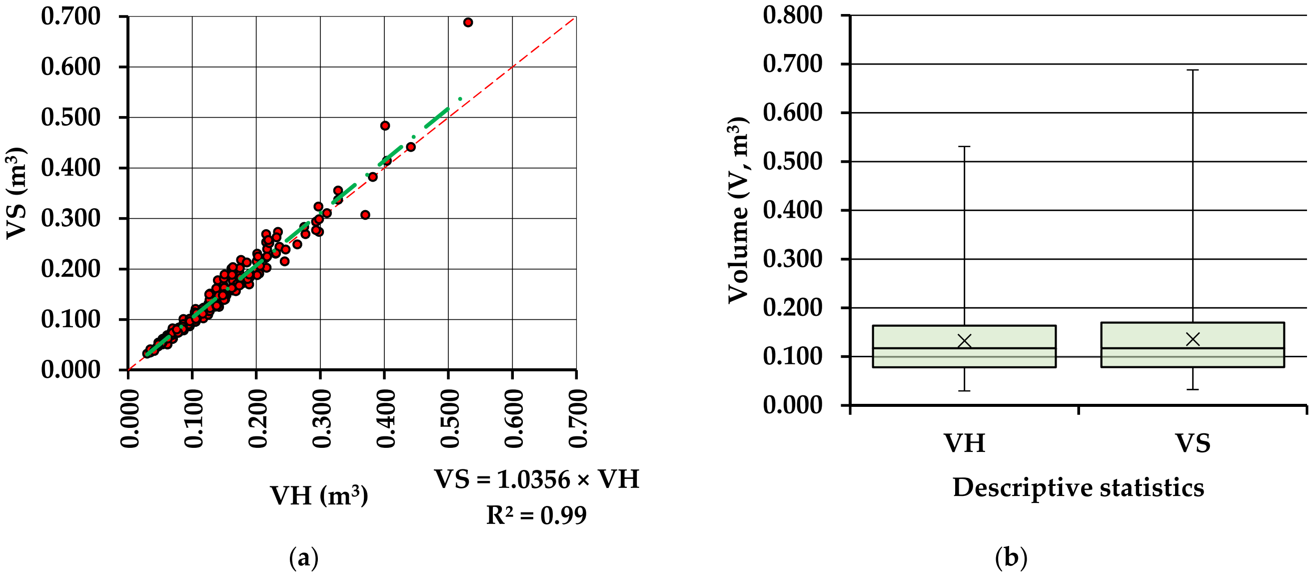


Figure 4. Descriptive statistics of the estimated log volume (E1): (**a**) A comparison between VS and VH, where the red dashed line stands for perfect agreement (equality line) and the green dot-dash line stands for the dependence relation between VS and VH fitted by RTO; (**b**) boxplots showing the summary of data distribution and the main descriptive statistics of the volume estimates, including the minimum, mean, median and maximum value.

As shown in Figure 4a, there was a relative agreement between the two volume estimates based on the same measurements, at least for the data range from ca. 0.030 to ca. 0.130 m^3. Beyond this threshold, the disagreement started to increase relative proportionally to the magnitude of volume.

Figure 5 shows the main descriptive statistics of the diameter and length measurements done by the two methods. The mean values of Dman and Dmeas diameters were of 22.86 and 22.89 cm, respectively, and the median values were of 22 cm. In the same order, the minimum values were of 10 and 9 cm, respectively, while the maximum ones were of 61 and 58 cm, respectively. On average, the values of log lengths were close, with a mean value of 306.27 in the case of Lman and a mean value of 305.92 cm in the case of Lmeas. Minimum and maximum values were also close, with values of 291, 290, 314, and 315 cm for Lman and Lmeas, respectively. For both variables, data ranges were close as values among the methods.

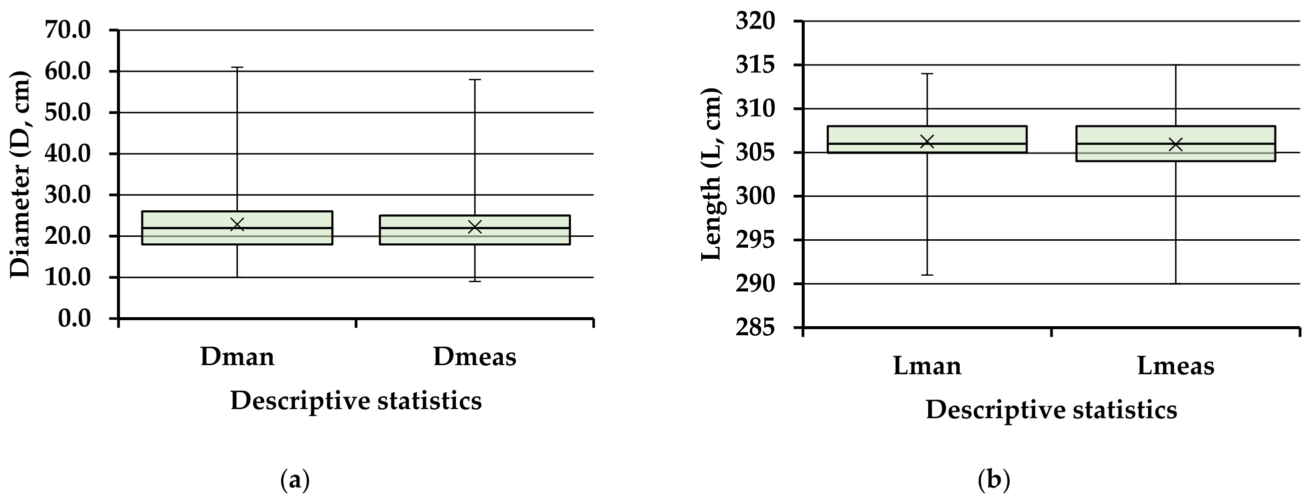
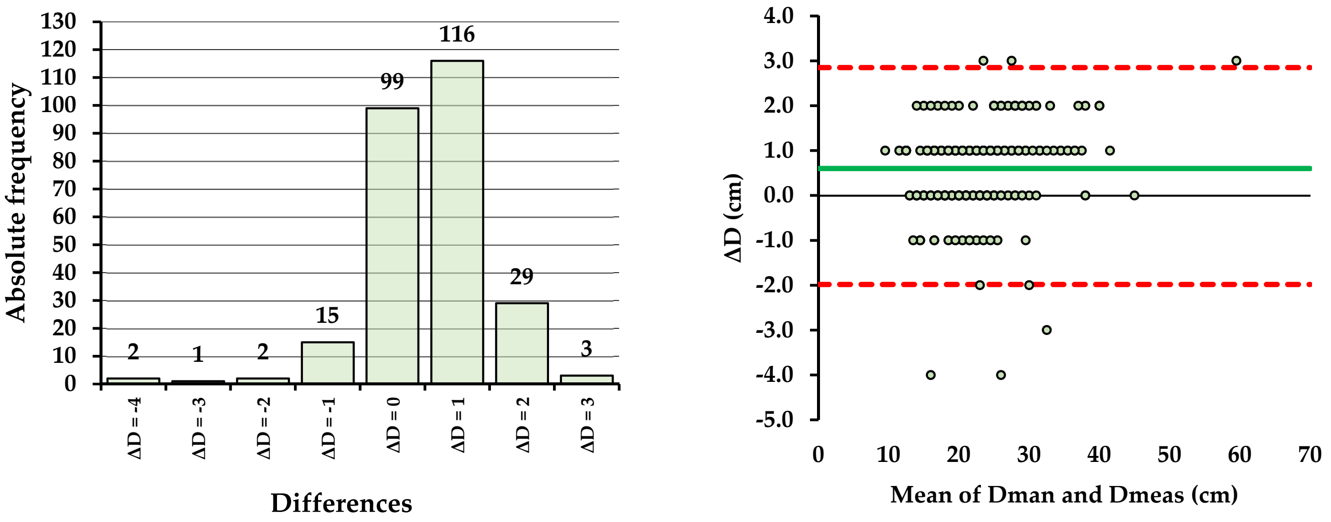


Figure 5. Descriptive statistics of the variables measured in E1: (**a**) Boxplots showing the main descriptive statistics for diameters; (**b**) Boxplots showing the main descriptive statistics for lengths.

3.1.2. Agreement between the Measurement Methods in E1

In terms of diameters, and taking as a reference the CM data, ca. 37% (99) of the observations were found in perfect agreement, 43% (116) were underestimated by 1 cm and ca. 6% (15) were overestimated by 1 cm (Figure 6). Approximately 86% of the observations were found in a difference range of ±1 cm, while the maximum absolute difference between the two methods was of 4 cm, in the form of an overestimation produced by the PM. The bias of the measurements was of 0.6 cm, meaning that the PM measured, on average, 0.6 cm less than the CM, and ca. 98% of the measurements were found between the limits of agreement. As proved by a Shapiro-Wilk test, data on differences did not follow a normal distribution.



(**a**) (**b**)

Figure 6. Agreement between the methods in terms of diameter measurement (E1): (**a**) Absolute frequency of differences (ΔD) between Dman and Dmeas; (**b**) Bland-Altman plot showing the differences plotted against the mean of paired measurements, the bias (green line), and the lower and upper limits of agreement (red dashed lines).

Figure 7, on the other hand, shows two important findings of data comparison. First of them is that the two datasets were strongly linearly-related as proven by the coefficient of determination (R^2 = 99.9), while the slope of regression through the origin equation was close to that of 1:1 represented by the red dashed line which stands for a perfect agreement (line of equality) between the two methods. Checking the data for heteroskedasticity by the Breusch-Pagan test indicated that the data was homoskedastic ($p > 0.05$), therefore it can be said with a confidence of 95% that the differences between measurements were not affected by other factors than the measurement methods themselves. This can be seen in Figure A1a which plots the squared residuals against the predicted Dmeas; as shown there was no increasing, decreasing, or other kind of trend in data as a function of predicted Dmeas.

Results of agreement between the two methods in terms of length are given following a similar data representation in Figures 8 and 9. More than 22% (60 observations) of the data indicated a perfect agreement between the two methods, close to 56% of the data (149 observations) were found to disagree by up to ±1 cm, and more than 95% (254 observations) were found to disagree by up to ±5 cm. The bias was of 0.3 cm, meaning that, on average, PM measured less by 0.3 cm. Approximately 94% (251 observations) were found in between the limits of agreement. Although there was a strong dependence relation between the length measured by the two methods (R^2 close to 1) and the slope of the regression line was very close to that of the perfect agreement, the data was quite spread indicating a higher degree of disagreement as compared to diameter measurement.

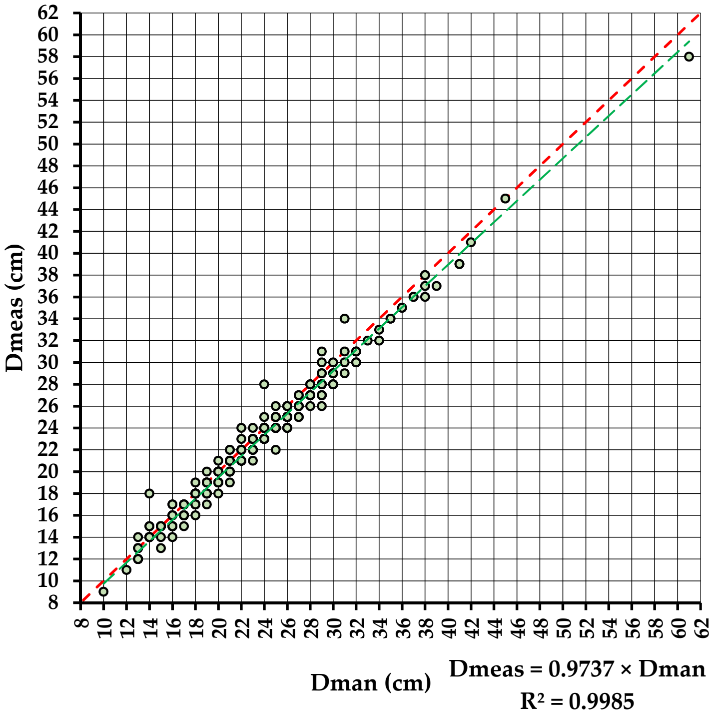
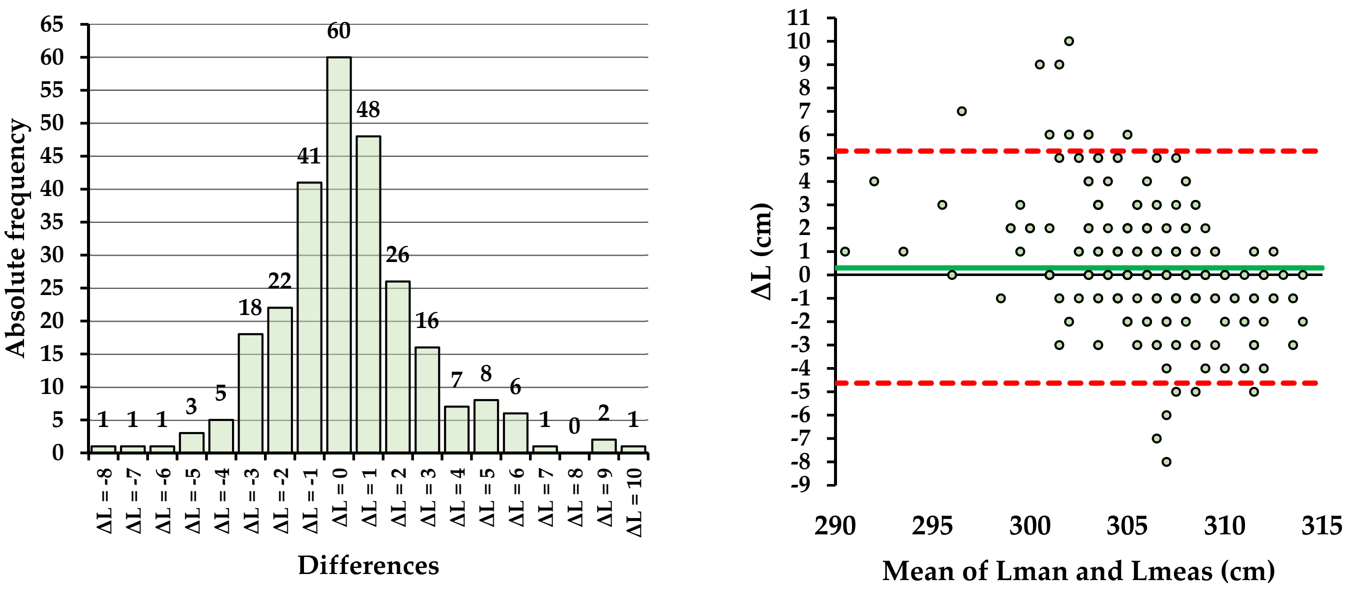


Figure 7. Relation between the diameters measured by the two methods (E1). Legend: red dashed line stands for perfect agreement and the green dashed line stands for the dependence relation between Dmeas and Dman fitted by RTO.



(**a**) (**b**)

Figure 8. Agreement between the methods in terms of length measurement (E1): (**a**) Absolute frequency of differences (ΔL) between Lman and Lmeas; (**b**) Bland-Altman plot showing the differences plotted against the mean of paired measurements, the bias (green line), and the lower and upper limits of agreement (red dashed lines).

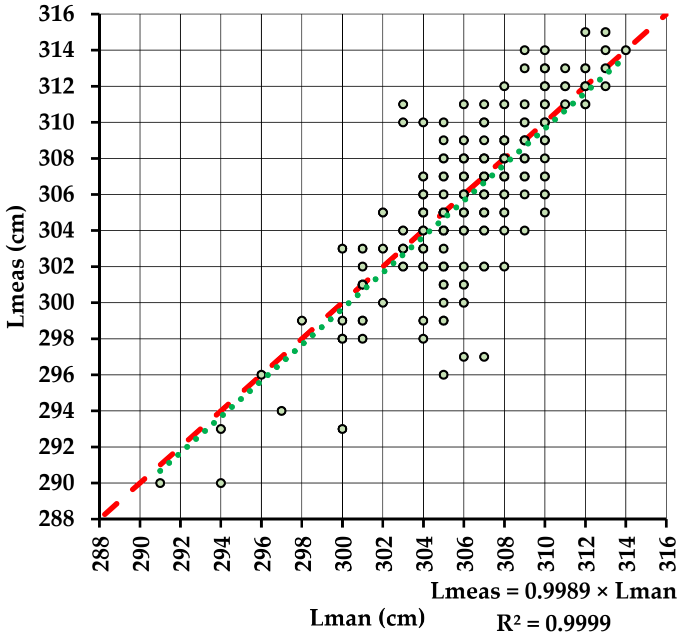


Figure 9. Relation between the lengths measured by the two methods (E1). Legend: red dashed line stands for perfect agreement and green dashed line stands for the dependence relation between Lmeas and Lman fitted by RTO.

Similar to the diameter measurement, the data on differences between the measurements of length did not follow a normal distribution; by the results of the Breusch-Pagan test the data was found to be homoskedastic ($p > 0.05$, Figure A1b).

3.1.3. Measurement Errors in E1

Table 1 shows the results of the error metrics for the first experiment (E1). Mean absolute error (MAE), Root Mean Squared Error (RMSE) and the Normalized Root Mean Squared Error (NRMSE) had values of less than 1 cm in the case of diameter measurements.

Table 1. Results on errors for the first experiment (E1).

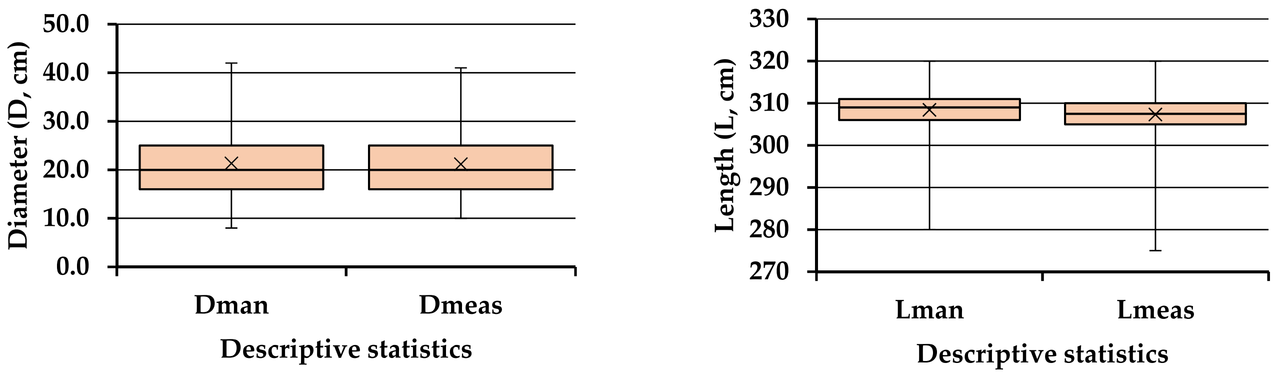
Error Metric	Diameter (cm)	Length (cm)
MAE	0.68	1.81
RMSE	0.96	2.55
NRMSE	0.02	0.10

For length measurement, MAE was less than 2 cm, RMSE was close to 2.5 cm and NRMSE was less than 1 cm. On average, these results indicate very low differences, therefore supporting a high agreement between the two methods, when approaching the problem at the sample size.

3.2. Experiment 2 (E2): Guided Measurement

3.2.1. Descriptive Statistics of E2

Table A2 shows the results of the normality check over the diameter and length variables for the second experiment (E2). Similar to the first experiment, none of the variables met the normality assumption. Figure 10, on the other hand, shows the descriptive statistics of the diameter and length variables as specific to the second experiment.



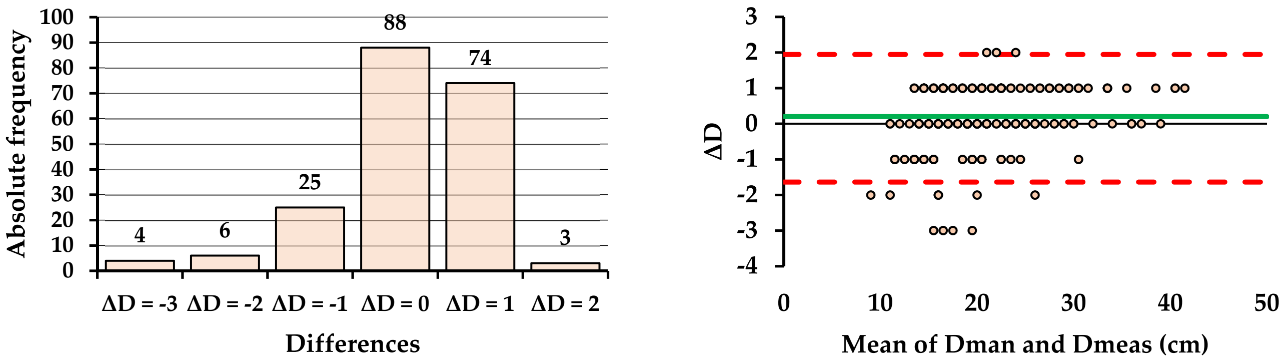
(**a**) (**b**)

Figure 10. Descriptive statistics of the measured variables (E2): (**a**) Boxplots showing the main descriptive statistics for diameters; (**b**) Boxplots showing the main descriptive statistics for lengths.

The mean diameters from CM and PM were close in value (21.3 and 21.2 cm, respectively); they were lower by approximately 1 cm compared to those from the first experiment, and varied in a lower range compared to E1. Lengths were also close in mean values between CM and PM (308.3 and 307.3 cm, respectively) and higher by approximately 2 cm compared to their counterparts from the first experiment. They varied in a wider range as opposed to E1.

3.2.2. Agreement between the Measurement Methods in E2

Figure 11 shows the results on absolute differences and agreement between diameter measurements as specific to the second experiment (E2). In terms of absolute differences, approximately 44% of the data was in perfect agreement, and close to 95% of the data was in a difference range of ±1 cm. These results indicate a greater agreement as opposed to that from E1. As proved by a Shapiro-Wilk test, data on differences did not follow a normal distribution (Table A2).



(**a**) (**b**)

Figure 11. Agreement of diameter measurement methods in E2: (**a**) Absolute frequency of differences (ΔD) between Dman and Dmeas; (**b**) Bland-Altman plot showing the differences plotted against the mean of paired measurements, the bias (green line), and the lower and upper limits of agreement (red dashed lines).

The bias was of 0.2 (Figure 11b), meaning that, on average, PM measured less by 0.2 cm, which was better than in E1 (one-third of the bias in E1), and close to 94% of the observations were found between the limits of agreement, which was similar to E1. The two datasets (Dman, Dmeas, Figure 12) were strongly linearly-related as proven by the coefficient of determination (R^2 = 99.8), while the slope of regression through the origin equation was close to 1 which indicates a high agreement between the two methods. Similar to E1, data was found to be homoskedastic (Figure A2a).

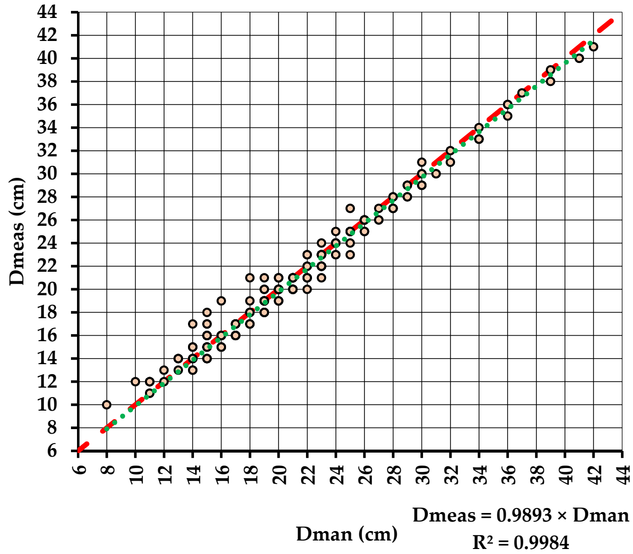


Figure 12. Relation between the diameters measured by the two methods (E2). Legend: red dashed line stands for perfect agreement and green dashed line stands for the dependence relation between Dmeas and Dman fitted by RTO.

Similar to diameters, the results of length measurement were better in terms of agreement (Figures 13 and 14) compared to those from E1. Close to 26% (53 observations) were in full agreement, which was higher compared to E1, 55% of the data (110 observations) were found to disagree by up to ±1 cm, which was close to E1, and 99% (198 observations) were found to disagree by up to ±5 cm. The bias was of 0.3 cm, meaning that, on average, PM measured less by 0.3 cm, which was the same as in E1, and 97% of the data (194 observations) were found within the limits of agreement. Similar to E1, there was a strong dependence relation between the length measured by the two methods (R^2 close to 1), and the slope of the regression line was very close to that of the perfect agreement; however, the data was quite spread indicating a higher degree of disagreement as compared to diameter measurement. The data on differences between the measurements of length did not follow a normal distribution; by the results of the Breusch-Pagan test the data was found to be homoskedastic ($p > 0.05$, Figure A2b).

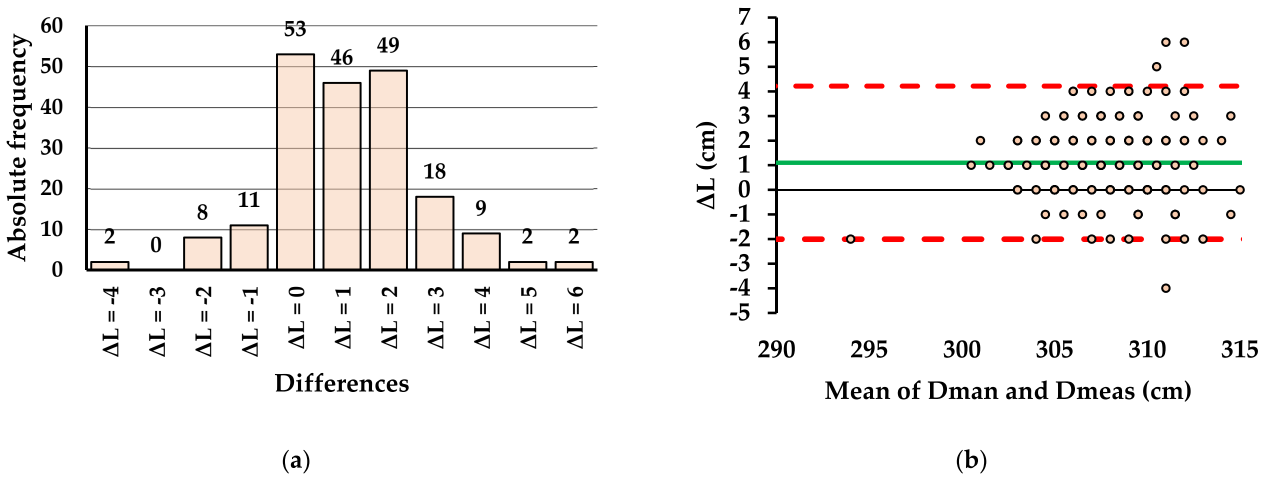


Figure 13. Agreement between the length measurement methods in E2: (**a**) Absolute frequency of differences (ΔL) between Lman and Lmeas; (**b**) Bland-Altman plot showing the differences plotted against the mean of paired measurements, the bias (green line), and the lower and upper limits of agreement (red dashed lines).

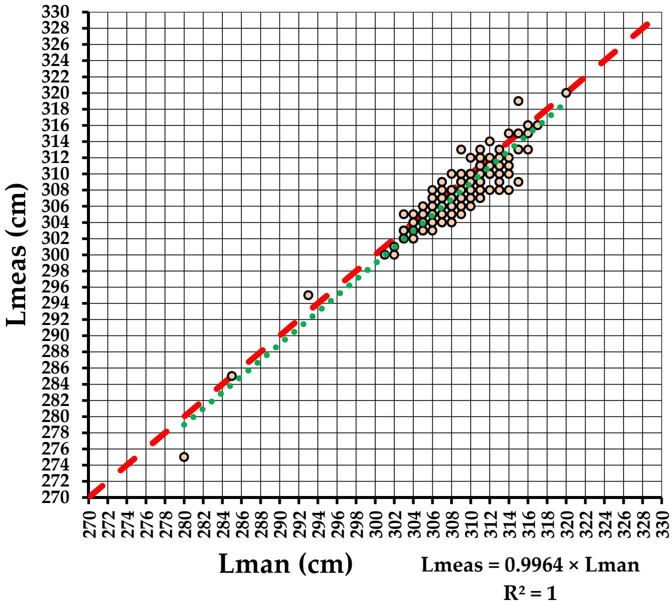


Figure 14. Relation between the lengths measured by the two methods (E2). Legend: red dashed line stands for perfect agreement and green dashed line stands for the dependence relation between Lmeas and Lman fitted by RTO.

3.2.3. Measurement Errors in E2

The results of measurement errors estimated for the second experiment (E2) are shown in Table 2. For both, diameter and length measurements they were lower although close to that of E1, with a diameter MAE, RMSE, and NRMSE of 0.65, 0.92, and 0.03 cm, respectively, and a length MAE, RMSE, and NRSME of 1.46, 1.93 and 0.04 cm, respectively.

Table 2. Results on errors for the second experiment (E2).

Error Metric	Diameter (cm)	Length (cm)
MAE	0.65	1.46
RMSE	0.92	1.93
NRMSE	0.03	0.04

The highest differences in errors of the E2 were those of length measurements. However, they accounted for less by 0.35 (MAE), 0.62 (RMSE), and 0.06 (NRMSE) cm, respectively, as compared to E1. Differences in the measurement errors of diameters were in range of 0.01 to 0.04 cm. Altogether, these results indicate that, at a sample level, the disagreement between the two ways of measuring the logs by the Measure app was rather small.

4. Discussion

The last decade has been characterized by a significant diversification in the development and testing of the non-conventional measurement tools, particularly in the tree biometrics measurement. LiDAR technology has been increasingly used in the form of highly-accurate expensive equipment to detect and measure biometrical characteristics of the individual trees, although several challenges related to the protocols to be used and to the diversity in forest conditions still remain [23,33], in addition to its high costs. Most likely, lower costs, equipment compactness, large-scale availability, and polyfunctionality, have led scholars to testing small-sized alternatives in tree [21,26,34,35] and log measurement [36]. Only some limited research has documented the accuracy of equipment capable of instantly provide the measurement results (e.g., [26]), and there is a lack of studies on the applicability and accuracy of close-range compact solutions to log measurement [36]. As a fact, most of the tested platforms still require more or less complicated workflows to process the data before producing the biometric estimates. The above-mentioned motivated this study to check if the general-purpose Measure application integrated with AR and LiDAR technologies could be a feasible solution to log biometrics measurement.

A first performance parameter that needs to be discussed in the measurement bias, characterizing the agreement between the conventional (CM) and phone-based (PM) measurements. For diameter measurement in E1, and E2 the bias was 0.6 and 0.2 cm, respectively, meaning that, on average, PM measured less (underestimated) than CM, irrespective of the experimental setup. This difference could be largely attributed to the fact that it was almost impossible to place the starting and ending points of the measurement right at the opposed ends of the log, characterizing a given diameter line. However, this may be changed by adjusting the positions of the starting and ending measurement points right after a measurement is done, therefore would require more time for measuring. While this approach was not taken in this study, it could hold the ability of improving the measurement agreement, by providing estimates close to those measured conventionally. In E1, the bias (0.6) was three times higher compared to E2 (0.2). Excluding random errors which could have been characterizing the CM and PM, as well as the effect of rounding the results of CM to the nearest centimeter, in E1 the higher bias value can largely come from the fact that there was not a perfect agreement among the points at which the log was touched by the caliper and those used to measure the diameter by the phone. As such, for scientific reference, the bias from E2 could be closer to the real agreement. For length measurements, there were no apparent differences between E1 and E2 in terms of bias. In both cases it was 0.3, which can be explained by fewer dimensional deviations as the end-edges of the log at its top were easier to appreciate visually, irrespectively of setting or not guiding marks. Still, there was an underestimation which can be attributed to at least two factors: the impossibility to place the measurement points exactly at the edges and the length of the log along the taper which could have been systematically higher in the mechanical measurement by tape. In relation to both, diameter and length estimates, ovality, curvature, and buttress of the logs may be additional factors explaining the differences found by this study.

There were significant differences in terms of diameter measurement agreement between E1 and E2. Guided measurement (E2) has led to 95% of the observations falling in a ±1 cm agreement range, while free-eye measurement (E1) accounted for 86% of the observations in this range. On the other hand, close to 98% of the data has fallen in an agreement range of ±2 cm, irrespective of the experiment, therefore the effect of the experimental setup was lower for this range of agreement. The frequency of observations falling in a ±5 cm agreement range for length measurement was close between E1 (95%) and E2 (99%). Since the data on both, diameter and length measurement differences has been proved to be homoskedastic, higher differences between measurements could be due to random errors in CM or to an improper setup of the starting and ending measurement points in PM. In addition, the condition of the logs under measurement could have been influenced by the PM accuracy since some logs were either wet or partially covered by snow (Figure 1).

Error metrics used in this study have indicated that there were no high differences between the experiments in terms of diameter measurement. Mean absolute error (MAE) was found to be of 0.68 and 0.65 cm for E1 and E2, respectively. This means that, on average, there was an absolute difference of close to 0.7 cm between CM and PM. Root mean squared errors (RMSE), on the other hand, were higher, accounting for close to 1 cm. However, RMSE error metrics are known to be driven in their magnitude by outlying data such as that characterizing high differences, as well as by the number of observations in a given sample [32]. Therefore, the values of MAE could be more closer estimates of the real differences. While for diameter measurement they were less than 0.7, for length measurement they were approximately two times higher, accounting for 1.81 and 1.46 cm in E1 and E2, respectively.

Compared to the results reported by other studies using mobile general-use platforms, the differences in terms of bias or error metrics found by this study were, in general, less. The study of [26] has reported biases of 0.3 to 0.36 cm for DBH measurements taken by a phone at a distance of 1.5 m. Their results agree with those of length measurements from this study, but were higher compared to those from the guided experiment (E2) for diameter measurement. RMSE values of 1.12 and 1.83–1.91 cm were found by [21] when estimating the DBH based on close-range photogrammetry and Google Tango technology embodied in mobile platforms, respectively. Also, by tree reconstruction from photographs taken with a mobile phone, the study of [35] indicated a general RMSE of 1.9 cm in DBH measurement, while the study of [34] has found RMSE and bias values in the range of 3.13–4.51 and −0.58 to 1.03, respectively, when extracting the DBH from point clouds collected with three applications installed on an iPad device. Having in mind the limitations of the RMSE as an error metric [32], a comparison with the above-mentioned studies indicates that the PM errors for diameter and length measurement were less and close, respectively, to the values indicated by other studies for DBH measurement.

Finally, a general evaluation of the applicability of the Measure app in log measurement needs to be considered. Given the results of this study, it seems that the PM option would be suitable for producing general estimates on log volume assuming that logs are piled and there is no access to them so as to properly implement CM. This is typical of landings where log piles are formed to save space and to facilitate loading and transportation of wood, and where a quantitative estimation of the wood could be in question before loading [1]. For such log grouping conditions, PM could prove indeed valuable for quickly measuring the diameters at the log ends. Assuming a bias of 0.6 cm, the measurements taken by PM could be corrected to better reflect reality, or other calibrations between the measurements could be in question depending also on the personal skills of the operators. However, for piled wood, there are some limits in capability which need to be addressed. First of all, the LiDAR range of the used platform is of 5 m, while the used app may take measurements only at ca. 2.5 m, as proved by some indoor experiments carried out by the authors. This means that the diameter of piled logs which are not accessible in this range cannot be measured by the tested solution. Secondly, for tall piles, it would be impossible to accurately locate both ends of a given log. Producing the final assortments at the felling area requires information about diameters and lengths of the logs [1], therefore PM could be used to pre-grade the delimbed stems before bucking. Of course, this would require diameter measurement taken over the felled stems, a measurement option which is different from that explored in this study. However, the accuracy for such applications seems to be acceptable based on the results of [26]. Accuracy in length, on the other hand, needs extra caution since failing to provide a length required for a given assortment may lead to downgrading a given log.

Log measuring is commonly done in hazardous work environments and it may burden the workers with the need to carry, use and store rather uncomfortable equipment. From these points of view, the use of the Measure app can add value by integrating the commonly used log measurement tools in a single lightweight device in which the personal functionalities can be extended by integrating those required by the measuring job. It also gives the possibility of saving the measurements and, more importantly, its use does not require direct contact with the logs, therefore it can contribute to safety enhancements. Compared to other apps and platforms such as those able to collect point clouds [22,24,36–38], the tested solution still shares some limitations in terms of data transfer, wood traceability, and transparency in the wood supply.

In relation to the experiments of this study, there are several other research directions that may be approached in the future. First of all, similar experiments should be set up to extend the sample size and to better infer the disagreements between the methods. Close to 500 logs were used in this study; however, it is likely that larger sample sizes will improve the rate of agreement between the methods by moving more pairwise measurements in higher agreement ranges. Accordingly, it is less likely that the bias between the two methods would change significantly, due to the reasons discussed above. Since replicability is of first importance in extending the PM, further studies could focus on the agreement of measurements as done by different operators. The logs measured in this study were limited to approximately 3 m in length and they were all processed from coniferous trees. To what extent the measuring capability may be extended to longer lengths, and how the measurement accuracy would respond to different species and operating conditions, need to be checked in the future to find a balance between the accuracy and capabilities of the measuring device.

5. Conclusions

Moving to digital solutions in log measurement is of the first importance for an efficient wood supply. Through two experiments, this study evaluated the agreement between the conventional and phone-based measurement having at its core the general-purpose Measure app developed by Apple, Augmented Reality, and LiDAR sensing capabilities of the iPhone 12 and 13 Pro Max platforms. The results indicate a good agreement between measurements, making this digital solution useful for several log-measurement applications, mainly by providing accurate results, improving ergonomics, and safety of measuring operations. Further studies could check if the accuracy of measurements would be enhanced by larger log samples and if there would be a good replicability of the method as of different operators. Also, finding a balance between capability and measurement accuracy by extending the study to longer log lengths, different species and operating conditions would be important to characterize the technical limitations of the tested method.

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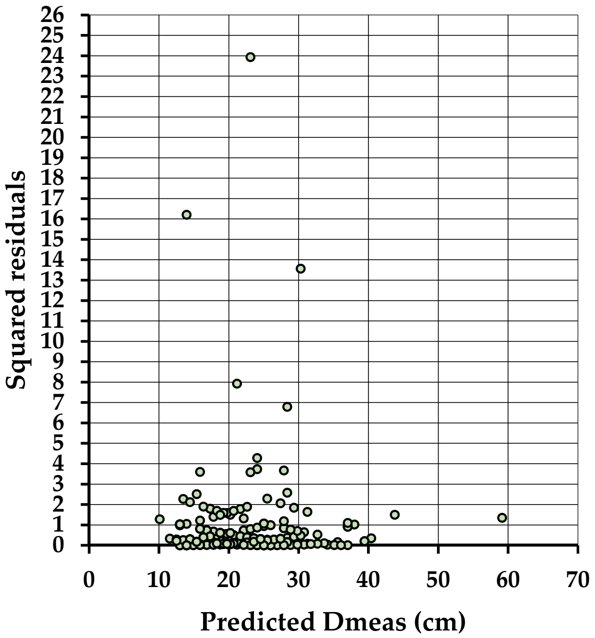
Conflicts of Interest: The authors declare no conflict of interest.

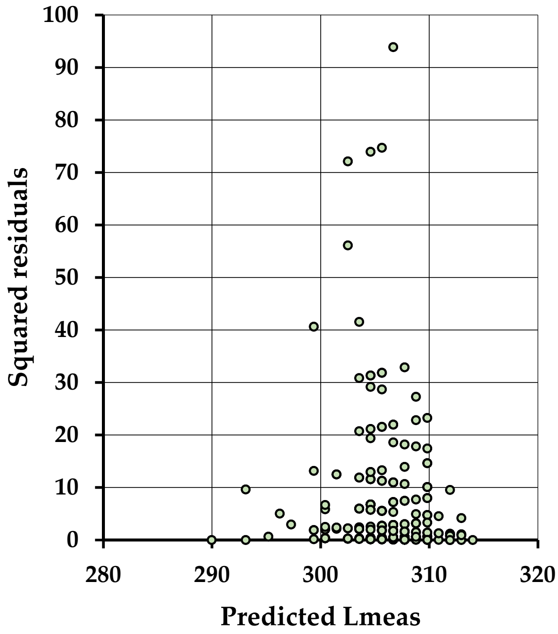
Appendix A

Table A1. Results of normality check for the first experiment (E1).

Statistic	VH	VS	Dman	Dmeas	Lman	Lmeas
W-stat	0.861984	0.831085	0.931375	0.938037	0.942384	0.966199
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
α	0.05	0.05	0.05	0.05	0.05	0.05
Diagnose	no	no	no	no	no	no



(**a**)

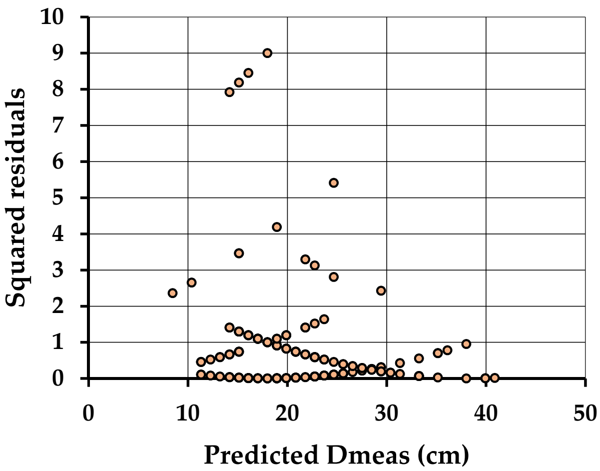


(**b**)

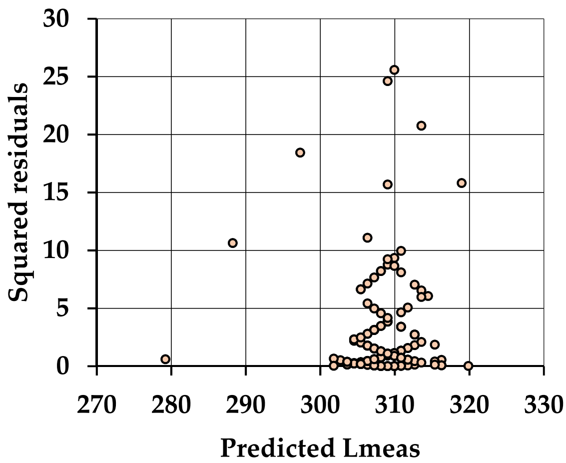
Figure A1. Results of the test for homoskedasticity (E1): (**a**) Plot of squared residuals against the predicted Dmeas (Note: data was homoskedastic by Breusch-Pagan test, $p > 0.05$); (**b**) Plot of squared residuals against the predicted Lmeas (Note: data was homoskedastic by Breusch-Pagan test, $p > 0.05$).

Table A2. Results of normality check for the second experiment (E2).

Statistic	Dman	Dmeas	Lman	Lmeas
W-stat	0.951711	0.83517	0.943546	0.824777
p-value	<0.001	<0.001	<0.001	<0.001
α	0.05	0.05	0.05	0.05
Diagnose	no	no	no	no



(**a**)



(**b**)

Figure A2. Results of the test for homoskedasticity (E2): (**a**) Plot of squared residuals against the predicted Dmeas (Note: data was homoskedastic by Breusch-Pagan test, $p > 0.05$); (**b**) Plot of squared residuals against the predicted Lmeas (Note: data was homoskedastic by Breusch-Pagan test, $p > 0.05$).

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