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# Time-of-Flight Adjustment Procedure for Acoustic Measurements in Structural Timber

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The effect of timber length on time-of-flight acoustic longitudinal measurements was investigated on the structural timber of four Spanish species: radiata pine (*Pinus radiata* D. Don), Scots pine (*Pinus sylvestris* L.), laricio pine (*Pinus nigra* Arn.), and maritime pine (*Pinus pinaster* Ait.). Time-of-flight longitudinal measurements were conducted on 120 specimens of dimensions 90 × 140 mm using three commercially available acoustic instruments (Sylvatest Duo, USLab, and Microsecond Timer). Time-of-flight data were initially obtained from the full-length (4 m) specimens, and then from the specimens cut to 3, 2, and 1 meter in length by successively cutting off 0.5 m from each end. The acoustic longitudinal velocity of the timber specimens of different lengths was also measured using a resonance-based acoustic method. The apparent acoustic longitudinal velocity for all species increased linearly as the timber length decreased from 4 to 1 meter. Acoustic velocity determined from time-of-flight data was significantly higher than the acoustic velocity determined using the resonance method, indicating systematic measurement errors associated with the time-of-flight instruments. Empirical models were developed for the relationships between time-of-flight measurements on timber specimens and timber lengths in the range of 1 to 4 m. Finally, a procedure was proposed to correct the time-of-flight data.

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## INTRODUCTION

Acoustic wave technology has long been used to assess the quality of wood material during wood processing, especially in structural timber grading (Bell *et al.* 1954; Jayne 1959). The principle of grading a piece of timber is based on predicting the modulus of elasticity (MOE) of wood through longitudinal acoustic wave measurements. Although the concept of acoustic timber grading has been validated (Sandoz 1989; Steiger 1996), it is important to note that acoustic measurements in timber are affected by many factors, such as moisture content, temperature, dimension of the timber piece, acoustic measurement systems, and instruments used (James 1961; Gerhards 1982; Bucur and Böhnke 1994; Wang 2013). Practical implementation of acoustic grading technology in the wood industry requires a full understanding of the impact of these physical and environmental conditions on the accuracy of acoustic measurements.

Several researchers have investigated the influence of cross-sectional size on the nondestructive prediction of the mechanical properties of timber. Specimen geometry has a significant effect on the wave propagation mode and acoustic velocity in structural

timber. Divos *et al.* (2005) found that the higher the width ratio between ends, the higher the longitudinal wave velocity (determined by the acoustic resonance-based method). Bucur (1984) conducted acoustic measurements on spruce (*Picea abies* (L.) Karst.) timber specimens with different width-to-thickness ratios (*b/h*) (from 1 to 14) and found that acoustic velocity was greatly affected by this ratio. The higher is the ratio, the lower is the velocity. In Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), as the cross-sectional size of square timber increased, the stress wave-based dynamic MOE deviation also increased (Wang 2013). It was concluded that different sizes of timber should not be graded together without making appropriate adjustments on dynamic MOE for the size effect. Similarly, Trinca and Gonçalves (2009) measured ultrasonic velocity on slash pine (*Pinus elliottii* Engelm.) and saligna gum (*Eucalyptus grandis* Hill. ex Maid.) using several operating frequencies. The authors reported that no significant difference was found between specimens of different sizes when operating frequencies were above 500 kHz.

The effect of specimen length on ultrasonic measurement has also been studied. Oliveira *et al.* (2006) investigated the variation of ultrasonic velocity in structural lumber of four different species; the authors reported a clear effect by the specimen length-to-wavelength ratio (*L/λ*) on the measured wave velocity when *L/λ* was less than 3. The wave velocity remained relatively unchanged when *L/λ* was greater than 3. Similarly, Bartholomeu *et al.* (2003) examined the influence of cross-sectional size and length on ultrasonic measurements in *Eucalyptus sp.* specimens and concluded that ultrasonic measurements can be performed when *L/λ* > 5. Depending on the operating frequencies of the ultrasonic sensors used, a minimum length of specimen should be specified. This requirement is included in the Brazilian non-destructive testing standard NBR 15521 (2007).

In another study, the longitudinal velocity was nearly constant when the length-to-width ratio was varied from 20 to 40 (Bucur 1984). The results of velocity measurements with a Sylvatest Duo device (22 kHz) on 161 specimens of missanda (*Erythrophleum spp.*) showed that length has a much greater influence than cross-section on time-of-flight (TOF) measurement. Apparent longitudinal velocity decreased by 83 m.s$^{-1}$ (1.65% with respect to the average value) as the length increased 1 m in the range of 1.6 m to 7.1 m (Arriaga *et al.* 2006).

The influence of specimen length and knottiness was studied using ultrasound measurements of Spanish Scots pine (*Pinus sylvestris* L.). As the specimen length increased 1 m, the apparent velocity decreased by 68 m.s$^{-1}$ in un-knotty timber and 83 m.s$^{-1}$ in knotty timber (Íñiguez *et al.* 2007), which are equivalent to 1.17% and 1.55%, respectively, with respect to the average value. Thus, knottiness affected TOF measurements within the same species.

Acuña *et al.* (2007) studied acoustic longitudinal wave velocity on 5 species; the authors proposed factors for angle and length adjustment of apparent velocity by species. In structural sawn timber, some correction factors were proposed for Spanish Scots and laricio pine (*Pinus nigra* Arn.) measured by the Sylvatest Duo (Arriaga *et al.* 2009). The apparent velocity of Spanish species can be corrected for length using a reference length of 2.7 m. The length effect is influenced by wood quality, such that lower quality has a greater influence (Íñiguez-González *et al.* 2015).

In the current study, TOF measurements were converted to a length-independent velocity value and compared with longitudinal wave velocity (determined by the acoustic resonance-based method). Previous works focused on length-to-width ratios above 20,

but this study used ratios from 11 to 44. The objectives of this research were as follows: to evaluate the impact of the timber length on acoustic velocity determined from TOF measurements in four coniferous species of Spanish provenance; to determine the systematic differences in these measurements, as determined by several commercially available ultrasonic/stress wave instruments; and to develop correction factors for adjusting TOF measurements for timber of different lengths.

## MATERIALS AND METHODS

### Specimen Preparation

The materials used in this study included 120 pieces of structural timber from four different pine species grown in Spain: radiata pine (*Pinus radiata* D. Don), Scots pine (*Pinus sylvestris* L.), laricio pine (*Pinus nigra* ssp. *salzmannii* (Dunal) Franco), and maritime pine (*Pinus pinaster* Ait. ssp. *mesogeensis* Fieschi & Gaussen). There were 30 pieces of each species. All specimens were air-dried and planed to 90 mm by 140 mm by 4000 mm.

The experiment was designed to test timber specimens of four different lengths, starting from an initial length of 4 m, then decreasing to 3 m, 2 m, and 1 m. Following the initial acoustic longitudinal measurements on the 4-m timber specimens, a 0.5-m section was cut from the ends of each piece of timber to obtain a length of 3 m. This procedure was repeated two more times to obtain timber specimens of 2 m and 1 m in length (Fig. 1). The length-to-width ratio varied from 44 to 11. All timber specimens were visually graded according to standard UNE 56544 (2011). This standard establishes the visual grade (MEG) for timber pieces with a width greater than 70 mm.
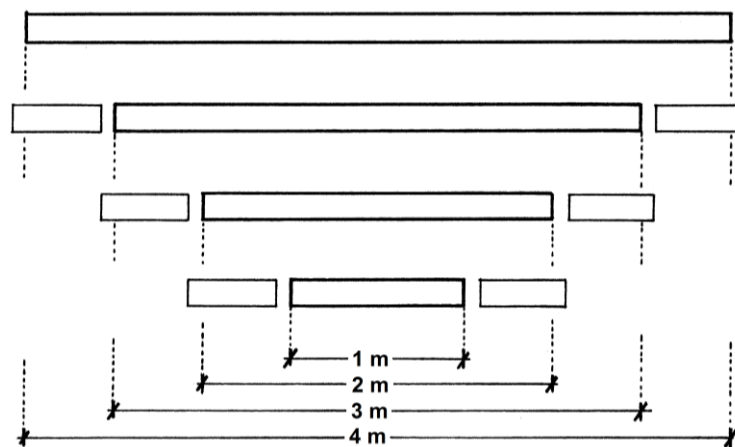


**Fig. 1.** Preparation of specimens

### Moisture Content and Density Measurements

The moisture content (MC) of the specimens was measured using an electrical resistance moisture meter (Gann RTU600, Gann Mess-u. Regeltechnik GmbH, Gerlingen, Germany), according to standard EN 13183-2 (2002). The average MC of the pieces was 10.9% with a coefficient of variation (COV) of 14.5%. The actual dimensions and weight of each specimen were measured, and the density was determined based on the weight and volume at the time of acoustic testing.
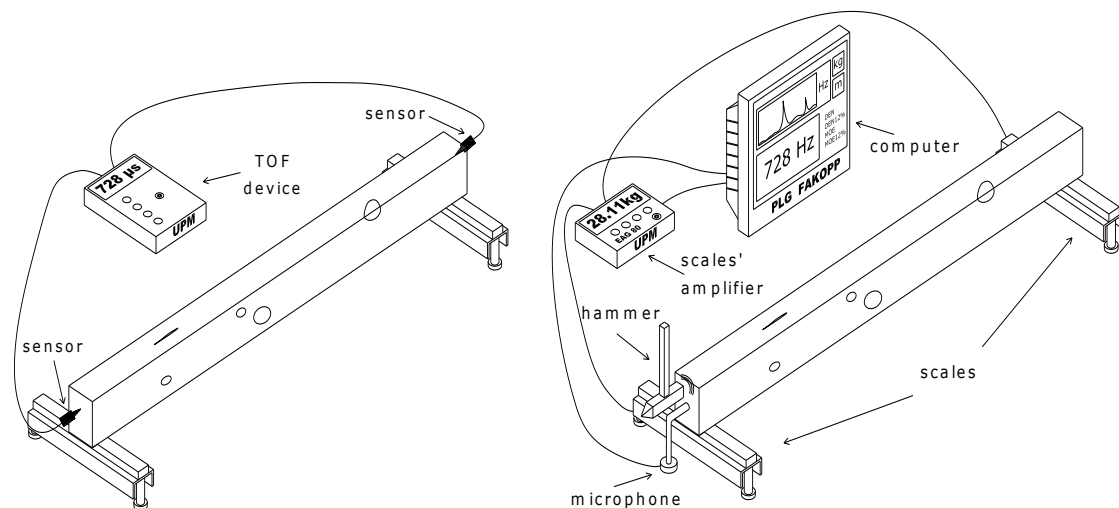
**Fig. 2.** Measurement setup (left – Time-of-flight device / right – resonance acoustic device)

## Time-of-Flight (TOF) Measurements

Time-of-flight acoustic longitudinal measurements (Fig. 2 left) were conducted on all specimens of four different lengths using three commercial instruments: 1) Sylvatest Duo (CBS-CBT, Paris, France) with conical sensors of 22 kHz frequency; 2) USLab (Agricef, Campinas, Brazil) with conical sensors of 45 kHz frequency; and 3) MicroSecond Timer (MST) (Fakopp Enterprise, Sopron, Hungary), an impact-induced stress wave timing device. Devices 1 and 2 are considered ultrasonic devices because the excitation is generated by a piezoelectric sensor with a specific ultrasonic frequency (sensors frequency). On the other hand, the device 3 is considered stress-wave device because the excitation is generated by a hammer.

Measurements were performed in a longitudinal direction (parallel to the grain) by placing one sensor on each end of the specimen. Average TOF data was obtained from five consecutive readings for each measurement. The acoustic longitudinal velocity (*V*) of the timber was determined from the following equation,

$$V = L/\Delta T \tag{1}$$

where *L* is the length of timber specimen (m) and $\Delta T$ is the average TOF (s).

In this study, the $L/\lambda$ values were in the range of 4.4 to 17.7 for the Sylvatest Duo instrument and 8.3 to 33.2 for the USLab instrument. The wavelength ($\lambda$) was deduced from the average wave velocity on 90 mm by 140 mm by 4000 mm specimens divided by the sensor frequency. The measurements were accepted because $L/\lambda$ fulfills the minimum recommended values (Bartholomeu *et al.* 2003; Oliveira *et al.* 2006; Trinca and Gonçalves 2009).

According to the Brazilian non-destructive testing standard NBR 15521 (2007), the specimen length must be greater than 0.60 m if the frequency of the sensor is between 20 and 30 kHz (in the case of Sylvatest Duo), and greater than 0.30 m if the frequency of the sensor is between 41 and 50 kHz (in the case of USLab). The shortest specimen in this study was 1 m long, which met the minimum length requirements recommended by this standard.

## Resonance Acoustic Measurement

The longitudinal wave velocity determined by the acoustic resonance-based method (Fig. 2 right) was measured on each specimen. The resonance-based acoustic (or vibration) measurement is a well-established, nondestructive testing technique for measuring long, slender pieces of wood, such as structural timber. In contrast to the TOF measurement approach, the resonance method stimulates many, possibly hundreds, of acoustic pulse reverberations in a piece, resulting in a very accurate and repeatable velocity measurement. Because of this accuracy, the velocity value obtained by the resonance-based measurement was used as a standard to validate the acoustic measurements made by the three TOF instruments. A Portable Lumber Grader (PLG) (Fakopp Enterprise, Sopron, Hungary) with a non-contact sensor (microphone placed in front of one end) was used to conduct resonance acoustic longitudinal measurements on each specimen. During the resonance measurement, each specimen was supported at two points near the ends. A longitudinal wave was induced into the timber through a hammer impact. The signal was recorded, and the first mode natural frequency ($f$, Hz) of the longitudinal wave signals was immediately obtained through the fast Fourier transformation (FFT) program installed on the device. The acoustic wave velocity ($V$) of each timber was then calculated using the following equation,

$$V = 2 \cdot f \cdot L \tag{2}$$
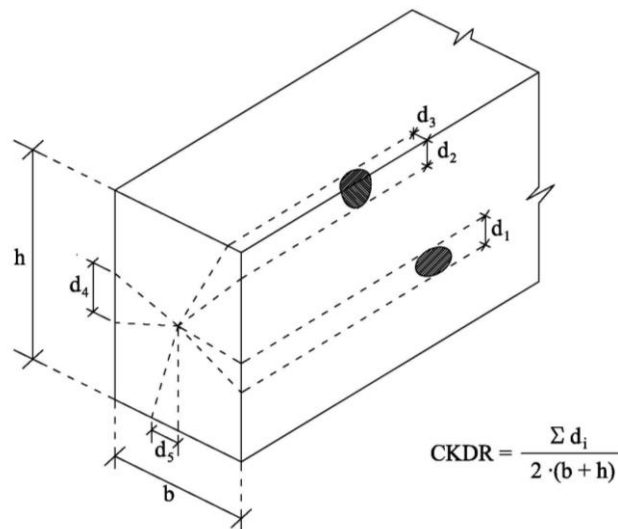
where $L$ is the length of the specimen (m).



**Fig. 3.** Concentrated knot diameter ratio; republished from Iñiguez (2007) with permission

## Concentrated Knot Diameter Ratio (CKDR)

The timber grading process assesses knottiness, which is characterized by the concentrated knot diameter ratio, or CKDR (Fakopp 2004). The knot diameter ratio (KDR) is defined as the knot diameter divided by the depth or width of the piece. The concentrated knot diameter ratio (CKDR) is the sum of the KDRs of the knots existing in any 15-cm length of a piece of timber. The distance to consider a knot cluster is defined as 15 cm by EN 844-9 (1997). The maximum CKDR observed on all 4 faces represents the quality of the piece (Fig. 3). The CKDR value was obtained for the worst 15-cm section in the entire piece, ranging from 0 to 1.

## Statistical Methods

Statistical analyses were performed with Statgraphics Centurion XVI software (Statpoint Technologies, Inc., Warrenton, VA, USA). The normal probability distribution was examined with the Kolmogorov-Smirnov test. ANOVA with LSD interval and a confidence level of 95% were used to study differences between velocities.

## RESULTS AND DISCUSSION

The mean TOF and coefficient of variation (COV) obtained from each type of acoustic longitudinal measurement, the mean of 30 pieces apparent velocities ($V_{ap}$) calculated using Eq. 1, and resonant velocities were obtained for each species (Table 1). All variables showed normal probability distributions.

Figure 4 shows an example of the mean acoustic apparent velocity and its standard deviation from one device and one species for different length groups and also shows the reference velocity (resonant velocity obtained from PLG). Using the TOF method, the measured apparent velocities tended to increase with decreasing timber length.
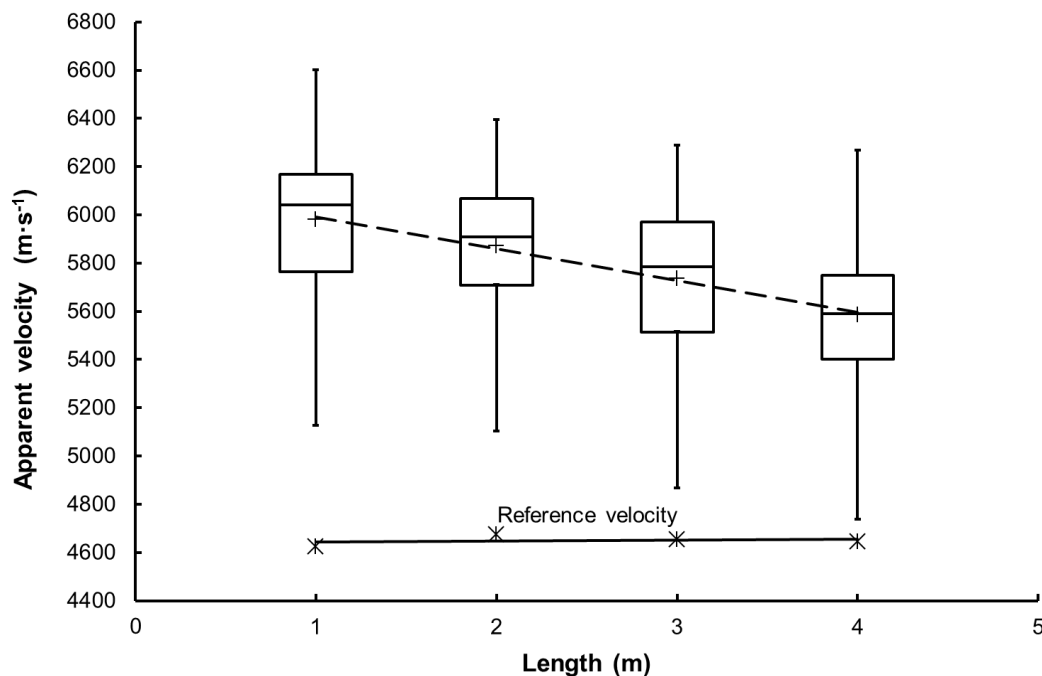


**Fig. 4.** Box plots for the USLab device and PLG reference velocity (laricio pine)

Figure 5 shows these values for every species and device. There were statistically significant differences in ultrasound wave and stress wave apparent velocities among timber specimens of different lengths. The apparent velocity varied 1.8 to 2.8% for each meter of length, depending on the device and species. In contrast, no significant difference was found in the resonant velocities of timber specimens of different lengths. The PLG velocity of Scots pine appeared to depend on length (Fig. 5b); however an ANOVA analysis showed no statistical significant differences between PLG velocities (P-Value = 0.37).

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**Table 1.** TOF and Apparent Velocities for Different Devices, Species, and Lengths

| Species | L (m) | Sylvatest Duo | | | USLab | | | MST | | | PLG | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean TOF (µs) | COV (%) | Mean $V_{ap}$ (m·s⁻¹) | Mean TOF (µs) | COV (%) | Mean $V_{ap}$ (m·s⁻¹) | Mean TOF (µs) | COV (%) | Mean $V_{ap}$ (m·s⁻¹) | Mean Vel (m·s⁻¹) | COV (%) |
| radiata Pine | 4 | 768 | 6.59 | 5227 | 704 | 6.57 | 5704 | 744 | 6.25 | 5392 | 4728 | 7.75 |
| | 3 | 564 | 6.38 | 5328 | 514 | 6.12 | 5839 | 554 | 6.05 | 5421 | 4748 | 8.13 |
| | 2 | 366 | 5.79 | 5434 | 336 | 5.50 | 5921 | 359 | 5.67 | 5539 | 4758 | 8.00 |
| | 1 | 177 | 6.02 | 5642 | 164 | 5.85 | 6116 | 176 | 5.82 | 5698 | 4767 | 8.34 |
| Scots Pine | 4 | 761 | 6.45 | 5275 | 700 | 6.62 | 5734 | 762 | 6.01 | 5270 | 4754 | 7.40 |
| | 3 | 562 | 6.35 | 5340 | 512 | 6.13 | 5867 | 563 | 5.48 | 5332 | 4826 | 7.02 |
| | 2 | 368 | 5.88 | 5434 | 336 | 5.67 | 5946 | 369 | 5.33 | 5409 | 4864 | 6.70 |
| | 1 | 180 | 6.39 | 5568 | 165 | 5.69 | 6088 | 183 | 5.75 | 5485 | 4902 | 6.54 |
| laricio Pine | 4 | 796 | 6.15 | 5072 | 723 | 6.08 | 5586 | 772 | 5.26 | 5229 | 4644 | 6.14 |
| | 3 | 581 | 6.17 | 5176 | 524 | 5.86 | 5735 | 558 | 5.33 | 5382 | 4654 | 6.25 |
| | 2 | 374 | 5.44 | 5348 | 341 | 5.07 | 5871 | 364 | 5.04 | 5496 | 4676 | 6.06 |
| | 1 | 185 | 5.63 | 5434 | 168 | 5.49 | 5980 | 175 | 6.30 | 5748 | 4625 | 7.10 |
| maritime Pine | 4 | 909 | 9.52 | 4435 | 837 | 9.77 | 4820 | 881 | 9.03 | 4570 | 3972 | 9.88 |
| | 3 | 656 | 9.15 | 4596 | 602 | 9.52 | 5014 | 644 | 8.65 | 4680 | 3980 | 9.43 |
| | 2 | 425 | 9.19 | 4721 | 387 | 9.09 | 5188 | 421 | 8.36 | 4765 | 4019 | 9.41 |
| | 1 | 208 | 8.48 | 4839 | 191 | 8.15 | 5283 | 202 | 7.66 | 4975 | 4014 | 9.65 |

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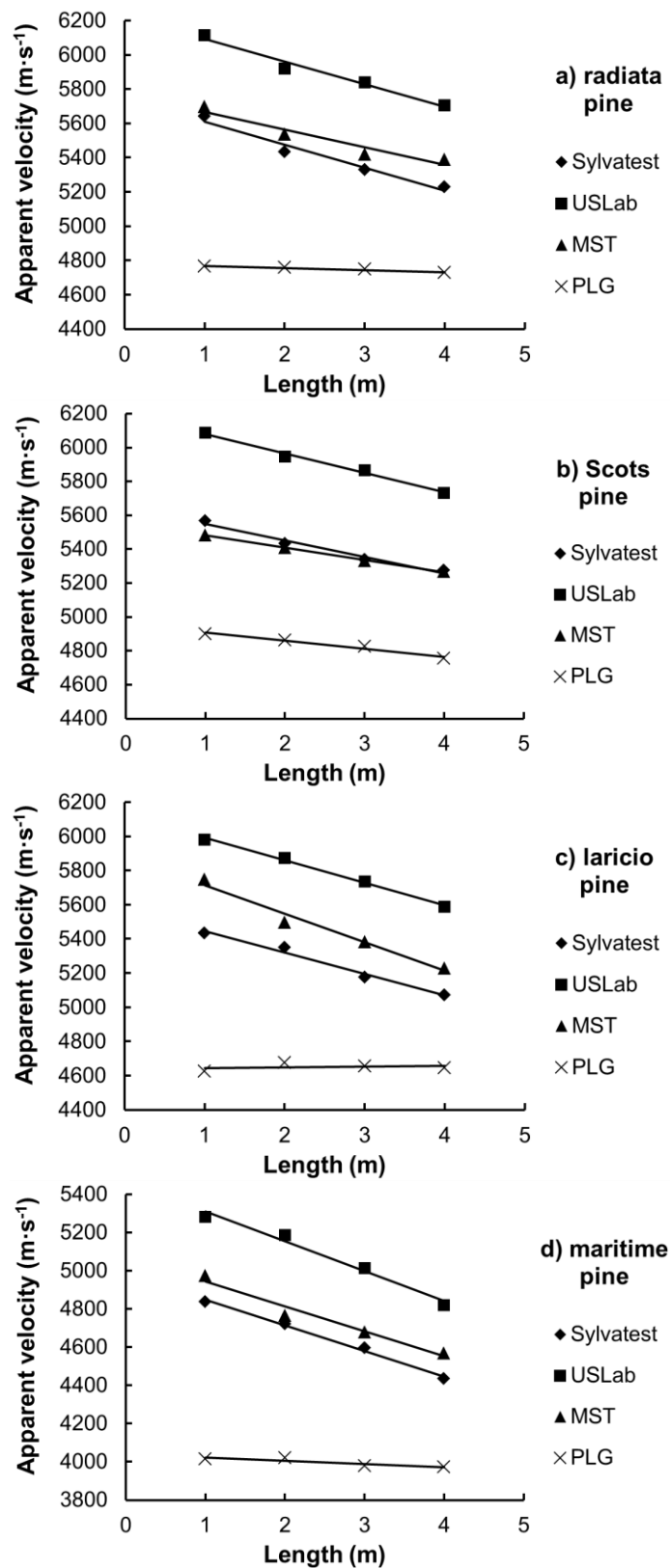


**Fig. 5.** Linear relationships between mean apparent longitudinal velocity and timber length (a-radiata pine; b-Scots pine; c-laricio pine; and d-maritime pine)

The apparent longitudinal velocities of the timber specimens calculated from TOF data were much higher than those obtained using the resonance method. The ratio between apparent velocity ($V_{ap}$) obtained from Sylvatest TOF and reference velocity obtained from the PLG device was calculated for every species. The mean value of the 4 species' ratios was 1.11 for timber 4 m in length and 1.20 for timber 1 m in length. In the same way, the mean ratios from USLab were 1.22 and 1.31, and in case of MST, 1.14 and 1.23, respectively. Frequently, longitudinal velocity from TOF is used to obtain the dynamic modulus of elasticity ($E_{dyn}$), based on Eq. 3 (for slender bars), which is a function of the square of velocity; thus the use of apparent velocities magnifies the error,

$$E_{dyn} = \rho \cdot V^2 \tag{3}$$

where $\rho$ is density (kg·m$^{-3}$) and $V$ is velocity (m·s$^{-1}$).

Table 2 shows the percentage of timber pieces that met the MEG requirements and average values of CKDR for each species and length group. The CKDR was much higher in maritime pine (with a higher percentage of rejection in visual grading), which could explain the different results obtained from maritime pine (Table 1). The influence of the species on TOF should actually be considered as species/grade factor.

**Table 2.** Visual Grade Percentage according to Standard UNE 56544, CKDR, and Density by Species

| Species | MEG grade (%) | Mean CKDR per Specimen Length Group | | | | Density | |
| | | 4 m | 3 m | 2 m | 1 m | Mean (kg·m$^{-3}$) | COV (%) |
|---|---|---|---|---|---|---|---|
| radiata pine | 66 | 0.17 | 0.15 | 0.13 | 0.12 | 511 | 6.35 |
| Scots pine | 97 | 0.13 | 0.13 | 0.12 | 0.10 | 518 | 8.72 |
| laricio pine | 63 | 0.18 | 0.17 | 0.16 | 0.14 | 549 | 9.08 |
| maritime pine | 17 | 0.28 | 0.25 | 0.23 | 0.16 | 573 | 9.72 |

**TOF Lag**

When linear regression analysis was performed between mean TOF (Table 1) and timber length ($L$) for each device and each species (Eq. 4), TOF showed a linear relationship with length from 1 m to 4 m (Table 3; Fig. 6).

$$TOF = a + b \cdot L \tag{4}$$

**Table 3.** Linear Regression Models for TOF *vs.* Timber Length

| Species | Sylvatest Duo | | | USLab | | | MST Fakopp | | |
| | *a* | *b* | $R^2$ | *a* | *b* | $R^2$ | *a* | *b* | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| radiata pine | -23.57 | 196.93 | 0.99 | -20.34 | 179.87 | 0.99 | -16.97 | 190.06 | 0.99 |
| Scots pine | -16.42 | 193.73 | 0.99 | -17.45 | 178.28 | 0.99 | -13.25 | 192.28 | 0.99 |
| laricio pine | -26.45 | 204.18 | 0.99 | -23.42 | 184.92 | 0.99 | -29.23 | 198.54 | 0.99 |
| maritime pine | -33.68 | 233.36 | 0.99 | -34.37 | 215.39 | 0.99 | -28.07 | 226.06 | 0.99 |

The linear regression equation showed a negative time for length equal to zero (Table 3). This time lag (TL; "*a*" in Eq. 4) depends on the device, species, and knottiness of the pieces of timber. Equation 5 determined the corrected TOF (TOF$_c$),

$$TOF_c = TOF + TL \tag{5}$$

where TOF is the ultrasound or stress wave time-of-flight in the longitudinal direction (µs) and TL is a constant depending on the device and species (summarized in Table 4). Table 4 also shows mean velocities averaged over the 4 timber lengths.
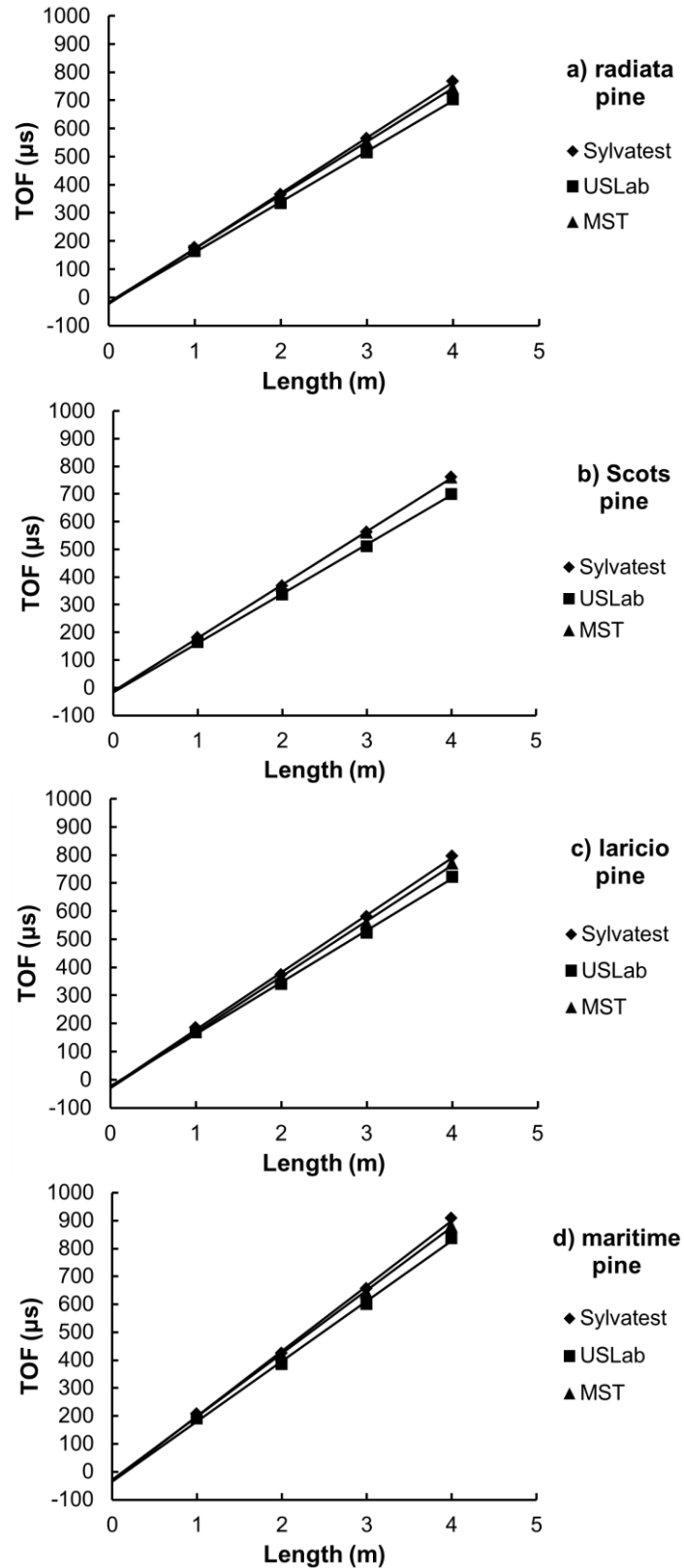
**Fig. 6.** Linear relationships between TOF and timber length (a-radiata pine; b-Scots pine; c-laricio pine; and d-maritime pine)
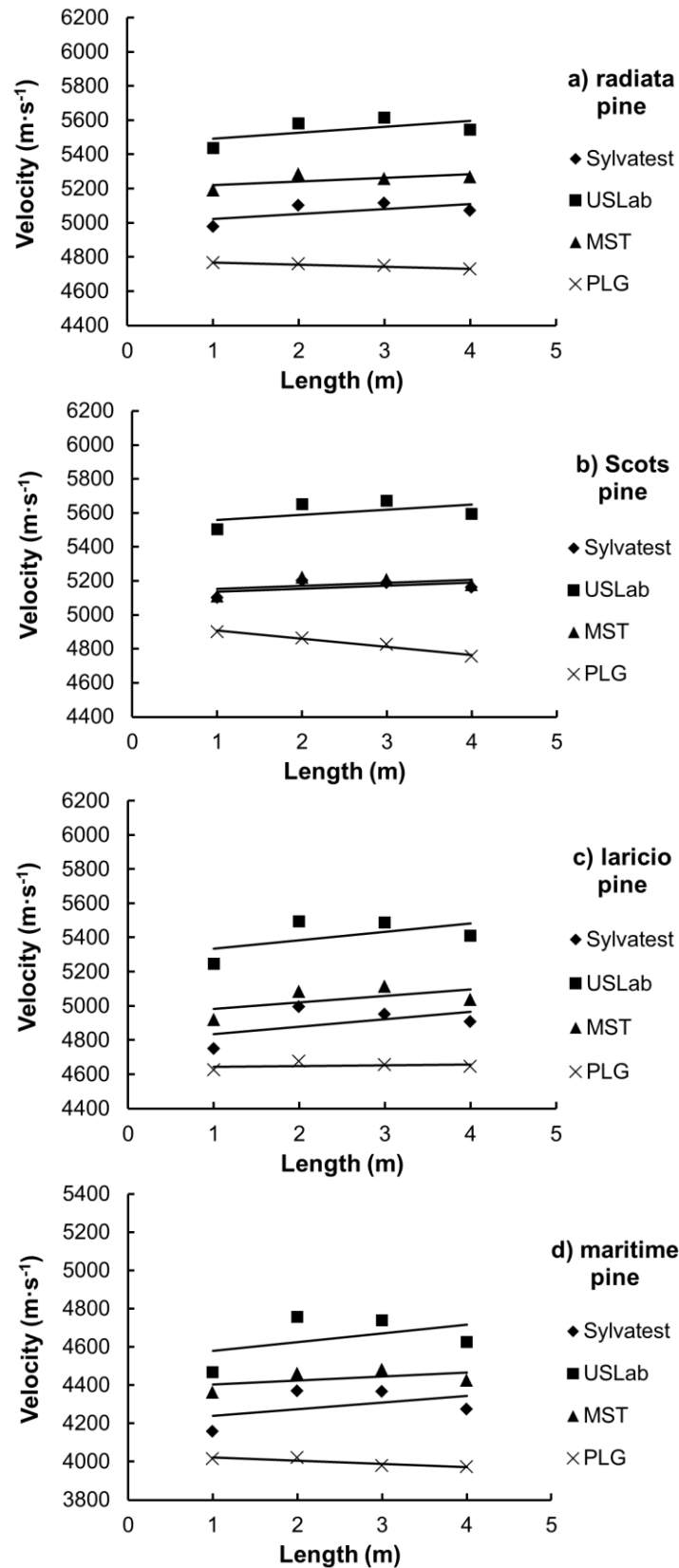
**Fig. 7.** Linear relationships between mean longitudinal velocity and timber length (a-radiata pine; b-Scots pine; c-laricio pine; and d-maritime pine)

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**Table 4.** Time Lags and Mean Velocities Obtained with Corrected TOF

| Species | Sylvatest Duo | | USLab | | MST Fakopp | | Vibration (PLG) |
|---|---|---|---|---|---|---|---|
| | TL (µs) | Mean $V$ (m·s$^{-1}$) | TL (µs) | Mean $V$ (m·s$^{-1}$) | TL (µs) | Mean $V$ (m.s$^{-1}$) | Mean Vel (m·s$^{-1}$) |
| radiata pine | 23.57 | 5066 | 20.34 | 5544 | 16.97 | 5252 | 4750 |
| Scots pine | 16.42 | 5163 | 17.45 | 5605 | 13.25 | 5180 | 4837 |
| laricio pine | 26.45 | 4900 | 23.42 | 5409 | 29.23 | 5039 | 4650 |
| maritime pine | 33.68 | 4292 | 34.37 | 4648 | 28.07 | 4434 | 3996 |

Based on linear regression analyses between velocities ($V$) obtained from TOF$_c$ and timber length, timber lengths between 1 and 4 m did not influence ultrasound or stress wave velocities (Fig. 7). Furthermore, the newly calculated acoustic velocities were closer to the reference velocities obtained from resonance-based method. The ratio between velocities achieved from TOF$_c$ and reference velocity obtained from PLG device was calculated for every species. The mean value of 4 species' ratios was 1.08, 1.18, and 1.11 for the Sylvatest, USLab, and MST devices, respectively.

The time lag varied from 13 to 34 µs, depending on the device and species (Table 4). One possible explanation for the differences between species is different CKDRs and densities. Preliminary statistical analyses were performed to examine the influence of these parameters on TL (Fig. 8). CKDR and density exerted influence on TL. In both cases, the higher the parameter, the higher the TL. Further studies should be conducted to analyze pieces from the same species with different knottiness and density.
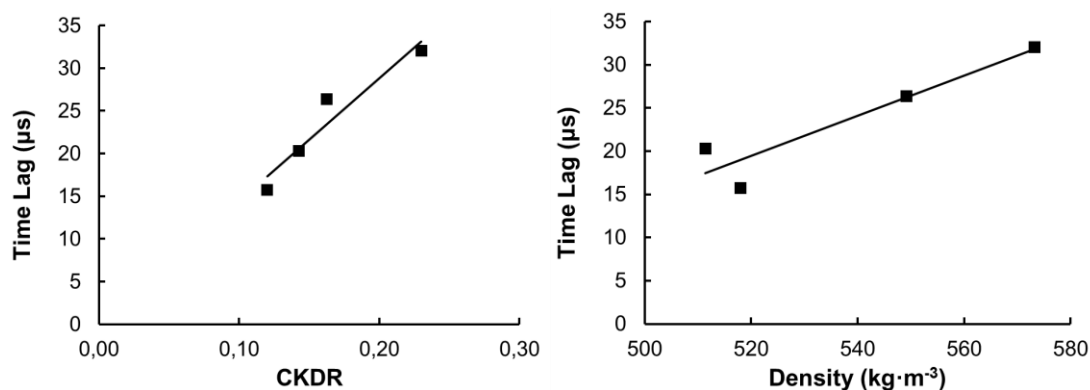


**Fig. 8.** Time lag *vs.* CKDR and time lag *vs.* density. All devices and species values were combined together.

When TOF was corrected for the time lag, the velocity was independent of length. However, this TL was different between species and even among the same species with different timber quality (knottiness). If TOF was not corrected by TL, the mean error (for 4 species and 3 devices) in calculating velocity was 10.56% in 1-m pieces and 2.97% in 4-m pieces. The error was calculated as a percentage of deviation of apparent velocity with respect to the velocity corrected by TOFc for each device and species. Therefore, TOF must be corrected for TL when calculating velocity using non-destructive techniques. The TL must be determined in every single case from the linear regression between TOF and length, using several measurements at different lengths in the same piece. In the case of structural assessment, it is not possible to cut out pieces of different

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lengths. Instead, the effect of length on ultrasound measurements made on the same or opposite faces could be tested.

## CONCLUSIONS

1. Time-of-flight acoustic longitudinal measurements showed a linear relationship with length (1 to 4 m), but TOF depended on time lag that varied with the device, species, and knottiness of the timber piece. If TOF was not adjusted to account for the time lag, the error in calculating velocity was around 11% in 1-m pieces and 3% in 4-m pieces. These errors are magnified when the square velocity is used to obtain dynamic modulus of elasticity in order to predict structural properties.

2. The time lag ranged from 13 to 34 μs. There was a relationship between time lag and knottiness of the species; larger CKDR values produced a longer time lag. Density had less of an influence than CKDR on the time lag.

3. Acoustic velocities obtained from corrected time-of-flight longitudinal measurements are closer to the reference measurements achieved using resonance-based method and show no length dependency. Thus, the time lag should be determined for each type of timber piece and for each commercial device, and the TOF determined by acoustic methods should be adjusted accordingly.

## ACKNOWLEDGMENTS

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