

Comparison of Optical Dendrometers for Prediction of Standing Tree Volume

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Abstract.—Enhanced sets of compatible stem profile equations were used with data collected from felled and standing pine trees to calculate tree volumes to various top merchantability limits. Standing trees were measured with the Criterion 400 Laser, Tele-Relaskop, and Wheeler Pentaprism. These measurements were used to compare accuracies of the optical dendrometers for the measurement of tree dbh and height and the prediction of tree volume from stem profile equations. The Criterion 400 Laser was more accurate for dbh and total height measurement than was the Tele-Relaskop or the Wheeler Pentaprism, but the accuracy differences are not significant in a practical sense. Mean percent differences in dbh measurement translated, in absolute units, to -0.05, +0.20, and -0.34 in. of the mean tree dbh for the Criterion 400, Tele-Relaskop, and Wheeler Pentaprism instruments, respectively. Mean percent differences in total height measurement translated, in absolute units, to 0.5, 1.6, and 1.7 ft, respectively, of the average tree height and were not practically different. The combined measurement data for dbh and dob_{16} indicated the Tele-Relaskop would produce more reliable volume results than the other instruments if the dendrometer measurements were used with form class volumes. Profile equations developed with felled-tree data produced the most consistent estimates of merchantable height and cubic foot volume to specified merchantable top limits. In general, the Criterion 400 produced the smallest mean differences in standing tree measurements and profile equation predictions of merchantable height and cubic foot volume. However, the Tele-Relaskop produced the most consistent tree measurement and profile prediction trends. The Wheeler Pentaprism was the least accurate of the three dendrometers.

The prediction of standing tree volume has traditionally involved destructive measurement methods, but these methods cannot be used in fragile forest ecosystems. Recent developments in telescopic and laser dendrometer instruments make it feasible to obtain upper stem measurements of standing trees in a non-destructive manner. However, the measurement accuracy and application technology of these instruments have not been evaluated. Bruce (1975) discussed some of the steps and limitations in evaluating accuracy of tree measurements made with optical instruments and emphasized that "... an adequate evaluation of their accuracy and that of less expensive devices is needed."

The Tele-Relaskop (Bitterlich 1978) is a precision, telescopic dendrometer that has been used, in limited industrial and research applications, to develop taper and volume functions for standing trees (Bitterlich 1984; Heske and Parker 1983; Parker 1983, 1997). Parker (1983, 1997) expanded the theoretical conoid concepts for

tree volume computations proposed by Bitterlich with polynomial taper functions, developed application software for the microcomputer, and compared volume and taper applications with conventional inventory procedures. Although Bitterlich (1984) stated the relative accuracy of the Tele-Relaskop as "percentage readings of tree diameters at an accuracy to the nearest 1/100 of 1 percent whilst readings for vertical dimensions only allow estimates to the nearest 1/10 of 1 percent," its accuracy for tree measurement and volume computation has not been established with documented research.

Laser dendrometers and distance measuring instruments are being developed, and some have been tested by the USDA Forest Service (Jasumback and Carr 1991). According to Carr (1992), laser technology of the Criterion model 400, manufactured by Laser Technology, Inc. (1991, 1992), has advanced to a point where accurate short- and long-range measurements are possible on non-reflective objects such as trees. In forestry applications, the Criterion 400 has been used for measuring tree heights and diameters, locating a specific height or diameter, selecting sample trees in variable plot inventories, measuring horizontal and slope distances, and determining coordinate azimuths and distances to defined targets (LaBau 1991, Liu *et al.* 1995). In engineering and

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mapping applications, the Criterion 400 has been evaluated by Moll (1992), Uren and Garner (1994), Byrnes *et al.* (1994), Pepling (1995), and Liu (1995). Although the accuracy of the Criterion 400 has been widely evaluated for surveying and engineering applications, there is little documented research pertaining to its accuracy in measurement of tree dimensions and no research on its accuracy for upper stem measurement and/or volume determination of standing trees.

The Wheeler Pentaprism (Wheeler 1962) has been used in forestry applications for obtaining upper stem diameters for many years. Although it does not have the telescopic optics of the Tele-Relaskop or sophisticated electronic circuitry of the Criterion 400, it can provide consistent estimates of upper stem diameters at heights determined by an attached clinometer.

Stem profile equations provide the most flexible methods of calculating tree volumes to specified merchantable top diameters from standing tree measurements. The technology of stem profile systems used by Burkhart (1977), Clutter (1980), Matney and Sullivan (1980 and 1982), and

Van Deusen *et al.* (1982) did not allow the use of upper stem diameters. Newer technology has produced compatible sets of stem profile equations (Matney and Parker 1992) that allow the prediction of tree volume to user-defined top merchantability limits.

This paper compares dbh and height measurements taken on standing trees with the Criterion 400 Laser, Tele-Relaskop, and Wheeler Pentaprism with direct measurements after felling. It also compares predicted volumes and heights from an enhanced set of compatible stem profile equations using the optical measurements on standing trees and the direct measurements on felled trees.

DATA COLLECTION

One hundred sample trees (*Pinus taeda* L.) were selected from a stand on the John Starr Memorial Forest that had been previously thinned from below to remove intermediate and suppressed trees. The sample trees ranged from 5.7 to 24.2 in. in dbh and from 53 to 109 ft in height (fig. 1). On each sample tree, breast height (4.5 ft above average ground level) and the top of the first 16.0-ft log

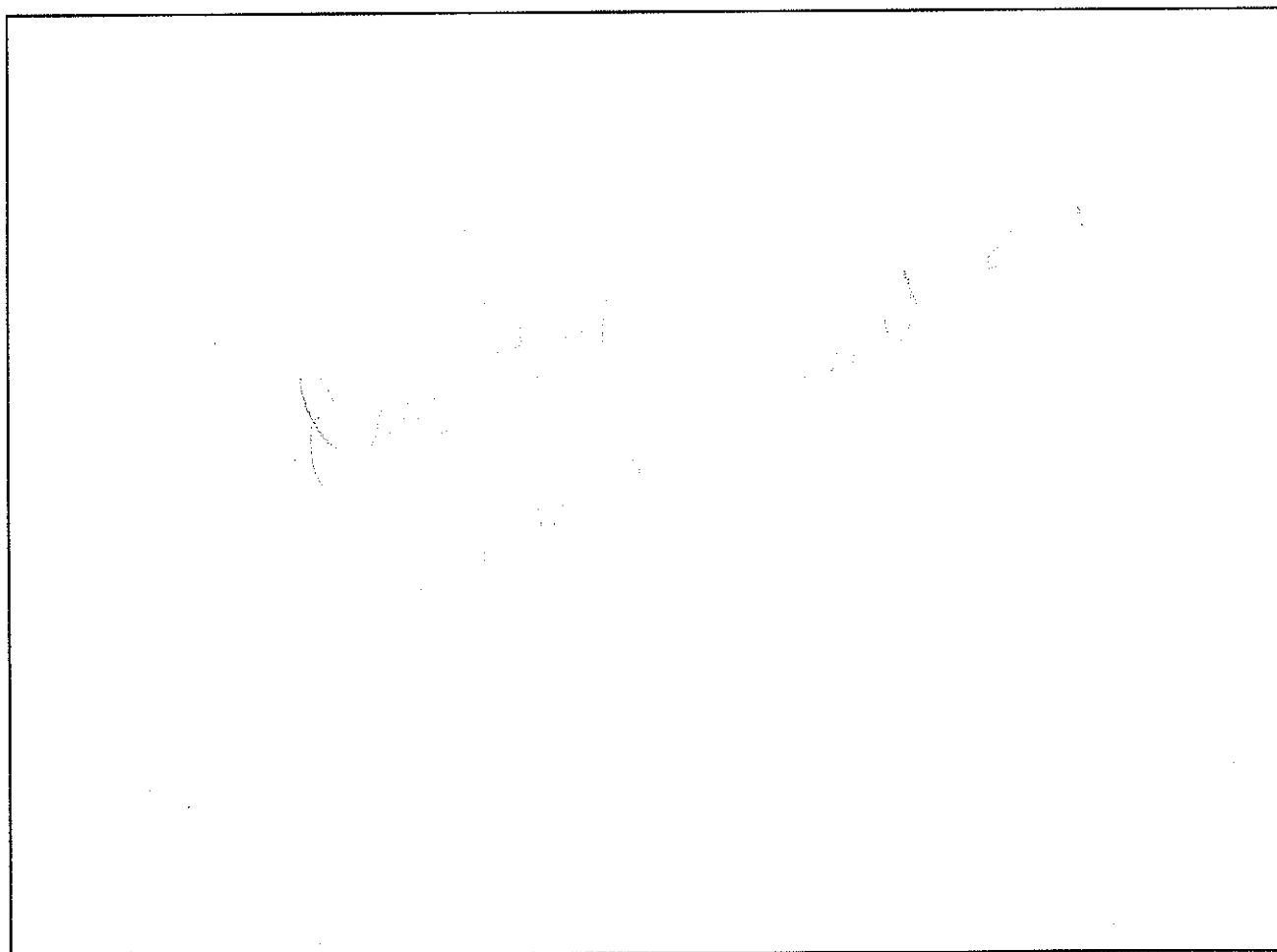


Figure 1.—Dbh and total height distribution of 96 sample loblolly pine trees measured with Criterion 400 Laser, Tele-Relaskop, and Wheeler Pentaprism dendrometers and felled for prediction of standing tree volumes. Dbh was measured with a caliper and height with a tape after felling.

(16.5 ft, assuming a 0.5-ft stump) were marked with a horizontal orange line and measured with a caliper.

Since operational inventories in fragile ecosystems would preclude the use of destructive measurement of felled-trees (at 4.0-ft intervals) and would possibly be limited by time and/or economics, stem measurement data obtained with optical or laser dendrometers would most likely be taken at stem intervals exceeding 4.0 ft. Therefore, dendrometer measurements of stem diameter (outside bark) and height were taken at breast height, at the top of the first 16.0-ft log, at two intermediate points spaced approximately equal between the top of the first 16.0-ft log and an estimated 3.0-inch top (ob), at an estimated 3.0-inch top (ob), and at total tree height. These stem measurement locations correspond to the dbh, four intermediate, and total height points described by Parker (1997) in previous applications of the Tele-Relaskop. Due to time and cost limitations, one member of the sample crew took all measurements with a specific instrument. The three resulting databases represent three different observers. Therefore, observer accuracy is confounded with instrument accuracy in a statistical sense. Observer effects were minimized, however, by a 2-day training period after which the author assigned each instrument to the observer who demonstrated the best proficiency and accuracy with the instrument. The author and two of four field technicians took all measurements, and each observer was deemed equal in the use of each instrument.

Sample trees were felled with a 0.5-ft stump. Diameters (ob) and bark thickness measurements were taken at the stump, 3.0 ft (2.5 ft above stump height), breast height (4.0 ft above stump height), and 4.0-ft intervals along the stem to the terminal bud. Diameters were measured to the nearest 0.1 in. with a steel caliper, and two bark thicknesses were obtained (one under each caliper arm) with a

bark gauge to the nearest 0.1 in. Total tree height was computed as the sum of the measurement intervals and the distance from the last diameter measurement to the tip.

DATA ANALYSIS

Although the primary objective of this study was to compare volume prediction accuracy of stem profile equations developed from optical dendrometer and felled-tree data, estimates of "point" measurement accuracy could be obtained for common measurements taken at breast height, 16.5 ft, and total height. The data sets were reduced to 96 trees because 4 trees in the felled-tree data set had at least one missing (inaccessible) measurement at or below breast height caused during the felling operation. Mean percent difference and standard error of the mean percent difference between the dendrometer measurements and felled-tree values were computed (table 1). The observed differences between felled-tree values and dendrometer measurements are expressed as a percentage of felled-tree value. Felled tree diameters at breast height and 16.5 ft were measured with a caliper in the same plane as viewed with the optical dendrometers.

During operational forest inventories, the measurements most commonly taken are dbh and merchantable height to a variable top diameter (ob) and/or total tree height. To simulate these measurement practices and to obtain sample tree volumes to variable top diameters, a compatible set of stem profile equations was developed to allow the prediction of outside- and inside-bark stem diameters at desired merchantability points from standing tree measurements of dbh and total tree height. The profile prediction system models used in this study are enhanced versions of the non-segmented, third-degree polynomial conditioned through the top (i.e., at $h=h_{\text{total}}$ or $X=h_i/h_{\text{total}}=1$, $dob_{hi}=0$) used by Parker (1983, 1997) and the

Table 1.—Comparisons of optical dendrometers for diameter and height measurement of standing loblolly pine trees where $\bar{d}$ is mean percent difference (observed difference as a percent of felled-tree value) and sd is the standard error of the mean percent difference (Basis: 96 trees)

Measurement	Statistic	Criterion 400	Tele-Relaskop	Wheeler Pentaprism
		Percent		
DBH ($dbh=14.1$ in.) ¹	$\bar{d}$ $s_{\bar{d}}$	-0.39 +0.53	+1.41 +0.40	-2.40 +0.57
DOB ₁₆ ($dob_{16}=12.6$ in.) ¹	$\bar{d}$ $s_{\bar{d}}$	-1.92 +0.60	+1.54 +0.66	-4.16 +0.56
Total Height ($H_t=92.8$ ft) ¹	$\bar{d}$ $s_{\bar{d}}$	+0.59 +0.45	+1.68 +0.78	+1.87 +0.3

¹Diameter measured with a caliper and total height with a tape after felling.

fifth-order polynomial constrained through dbh and the top merchantability limit (i.e., $dob_m/dbh=1$ when $h_i=4.5$ ft and dob_{h_i} = merchantable top dob when $h_i=h_m$) used by Matney and Parker (1992).

The set of profile prediction system models applied to the felled and optical dendrometer tree data where b_1 and b'_1 are regression coefficients for outside and inside bark, respectively, are:

At stump height of 0.5 feet (i.e. $h_i = 0.5$ ft)

$$\frac{dob_{0.5}}{dbh_{ob}} = b_1 \left(\frac{1}{dbh_{ob}} \right) + b_2 \quad (1)$$

$$\frac{dib_{0.5}}{dbh_{ob}} = b'_1 \left(\frac{1}{dbh_{ob}} \right) + b'_2$$

At dbh: dbh_{ob} to dbh_{ib} conversions (i.e. $h_i = 4.5$ ft)

$$\frac{dbh_{ib}}{dbh_{ob}} = b_3 \left(\frac{1}{dbh_{ob}} \right) + b_4 \quad (2)$$

Below breast height (i.e. $h_i < 4.5$ ft)

$$\begin{aligned} y_i &= 1 + b_5(x_i - w_i) + b_6(x_i^2 - w_i^2) \\ z_i &= 1 + b'_5(x_i - w_i) + b'_6(x_i^2 - w_i^2) \end{aligned} \quad (3)$$

where:

$$\begin{aligned} y_i &= \frac{dob_{h_i}}{dbh_{ob}} & z_i &= \frac{dib_{h_i}}{dbh_{ob}} \\ x_i &= \frac{h_i}{h_i} & w_i &= \frac{4.5}{h_i} \end{aligned}$$

Above breast height (i.e., $h_i \geq 4.5$ ft)

$$\begin{aligned} y_i &= \frac{x_i - 1}{w_i - 1} + b_7 \left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)} \right] + b_8 \left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)} \right] \\ z_i &= \frac{x_i - 1}{w_i - 1} + b'_7 \left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)} \right] + b'_8 \left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)} \right] \end{aligned} \quad (4)$$

Bark relationship above breast height (i.e., $h_i \geq 4.5$ ft)

$$\left(\frac{dib_{h_i}}{dob_{h_i}} \right) = \left(\frac{dbh_{ib}}{dbh_{ob}} \right) e^{b_9 \left[\frac{dbh_{ob}}{dob_{h_i}} - 1 \right]^{0.25}} \quad (5)$$

Equation (1) predicts stump diameter (ob and ib) at 0.5 ft aboveground from dbh_{ob} . Equation (2) predicts dbh_{ib} from dbh_{ob} . Equation (3) is a constrained, second-degree polynomial, profile model to predict stem diameter (ob and ib) between stump height and breast height. Equation (3) is constrained through breast height so that at $h_i=4.5$ ft, $dob_{hi}/dbh_{ob}=1$. Equation (4) is a constrained, third-degree polynomial, profile model to predict stem diameter (ob and ib) between breast height and total tree height. Equation (4) is constrained through both breast and total height so that at $h_i=h_{total}$, $dob_{hi}=0$ and $dib_{hi}=0$. Thus, Equation (4) is constrained through ratio estimate points 1 and 0. Equation (5) predicts the dib/dob (i.e., bark) relationship along the upper stem above breast height. The exponent in Equation (5) was fixed at 0.25 because attempts to fit that parameter often cause convergence problems with some nonlinear procedures. Equation (5) was developed from the felled-tree data for use with the dendrometer data sets when an inside bark diameter is needed. Computing the bark relationship with Equation (5) is more efficient than computing the ob and ib values in two steps with Equation (4).

PROFILE EQUATION RESULTS

The resulting profile equations to predict diameters below breast height and the bark relationship above breast height for the felled tree data set, where $s_{y,x}$ is the standard error of prediction and I^2 is the index of fit for 96 trees, are:

At stump height of 0.5 feet (i.e., $h_i = 0.5$ ft)

$$\frac{dob_{0.5}}{dbh_{ob}} = 0.9364 \left(\frac{1}{dbh_{ob}} \right) + 1.1294 \quad \text{with } n=96, s_{y,x}=0.0708 \quad \text{and } I^2 = 0.1165 \quad (6)$$

$$\frac{dib_{0.5}}{dbh_{ob}} = -0.0149 \left(\frac{1}{dbh_{ob}} \right) + 1.0342 \quad \text{with } n=96, s_{y,x}=0.0697 \quad \text{and } I^2 = 0.0000$$

At dbh: dbh_{ob} to dbh_{ib} conversions (i.e., $h_i = 4.5$ ft)

$$\frac{dbh_{ib}}{dbh_{ob}} = -0.3815 \left(\frac{1}{dbh_{ob}} \right) + 0.8896 \quad \text{with } n=96, s_{y,x}=0.0295 \quad \text{and } I^2 = 0.1124 \quad (7)$$

Below breast height (i.e., $h_i \leq 4.5$ ft)

$$y_i = 1 + -7.1727(x_i - w_i) + 45.3420(x_i^2 - w_i^2) \quad \text{with } n=192, s_{y,x}=0.0567 \quad \text{and } I^2 = 0.6691 \quad (8)$$

$$z_i = 1 + -8.0688(x_i - w_i) + 62.1590(x_i^2 - w_i^2) \quad \text{with } n=192, s_{y,x}=0.0572 \quad \text{and } I^2 = 0.6778$$

where: $y_i = \frac{dob_{h_i}}{dbh_{ob}} \quad z_i = \frac{dib_{h_i}}{dbh_{ib}}$

$$x_i = \frac{h_i}{h_t} \quad w_i = \frac{4.5}{h_t}$$

Bark relationship above breast height (i.e., $h_i \geq 4.5$ ft)

$$\left(\frac{dib_{h_i}}{dob_{h_i}} \right) = \left(\frac{dbh_{ib}}{dbh_{ob}} \right) e^{0.0642 \left[\frac{dbh_{ob}}{dob_{h_i}} - 1 \right]^{0.25}} \quad \text{with } n=1,600, s_{y,x}=0.0368 \quad \text{and } I^2 = -0.5791 \quad (9)$$

The parameter estimates and statistics of fit for Equation (4) developed from the felled-tree and dendrometer data taken above breast height, are shown in table 2. Optical and laser dendrometers are most commonly used to obtain outside bark diameters for above-breast height stem locations because of stump visibility limitations, so only the coefficients for Equation (4) were obtained for the dendrometers.

Table 3 shows the statistical significance of the profile system equation for outside bark prediction above breast height (Equation 4) for the felled tree, Criterion 400, Tele-Relaskop, and Wheeler Pentaprism data sets. The regression coefficients of each data set equation were judged significantly different from zero, and each data set equation was judged significantly different from other equations at the 0.01 level.

Profile equations were fitted to the felled tree data set and to the three sets of optical dendrometer data. Heights to

various diameters and cubic foot volumes were predicted with the profile equations and compared to the computed, felled-tree volumes. Table 4 shows the mean percent differences between heights and volumes computed with the profile system equations and measured felled-tree values. Cubic foot volumes and merchantable heights of the felled trees were computed to 0, 3, 6, 8, and 10 inch top diameters (ob) using Smalian's formula and linear interpolation of intermediate bolt diameters. Percent difference is the arithmetic difference between the computed value from the profile system equation(s) and the measured felled-tree value expressed as a percentage of felled-tree value. Equation (4) coefficients for each of the felled-tree and dendrometer data sets (table 2) were used to compute upper stem diameters at 4.0-ft intervals above breast height. Diameters below breast height (0.5 and 3.0 ft) were computed for all data sets with felled-tree Equations (6) and (8). Bolt length to a specified top merchantability limit that was contained within a bolt was obtained by linear interpolation of computed endpoint bolt diameters.

Table 2.—Tree profile prediction system parameter estimates* and statistics of fit for felled-tree and optical dendrometer (above-breast height) data for loblolly pine where ob and ib are outside and inside bark, n is number of observations, $s_{y,x}$ is the standard error of prediction, and P is the index of fit

Parameter	Felled-tree		Criterion 400	Tele-Relaskop	Wheeler Pentaprism
	ob	ib	ob	ob	ob
b_7	1.74963	1.1616	1.8016	1.6914	1.9809
b_8	-1.5837	-1.3391	-1.5607	-1.5266	-1.6567
n	1,699	1,699	477	476	470
$s_{y,x}$	0.0457	0.0484	0.0642	0.0623	0.0508
P^2	0.9665	0.9651	0.9589	0.9624	0.9737

* for above-breast height tree profile equations:

$$y_i = \frac{x_i - 1}{w_i - 1} + b_7 \left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)} \right] + b_8 \left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)} \right]$$

$$z_i = \frac{x_i - 1}{w_i - 1} + b_7' \left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)} \right] + b_8' \left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)} \right]$$

where:

$$y_i = \frac{dob_{h_i}}{dbh_{ob}} \quad z_i = \frac{dib_{h_i}}{dbh_{ob}}$$

$$x_i = \frac{h_i}{h_t} \quad w_i = \frac{4.5}{h_t}$$

Table 3.—Statistical significance of the profile prediction system equation¹ for outside bark measurements above-breast height for the felled-tree and optical dendrometer databases (Basis: 96 loblolly pine trees)

Data Set	SS _e	df	F _{calc} ²	Prob
1Felled-tree	3.54293	1,696	7076.36	<0.0001
2Criterion 400 Laser	1.95140	474	715.54	<0.0001
3Tele-Relaskop	1.83615	473	830.47	<0.0001
4Wheeler Pentaprism	1.20306	467	1016.60	<0.0001
Pooled1234	8.71041	3,116	1.0188	<0.0001
Pooled12	5.56685	2,172	1.0123	<0.0001
Pooled13	5.38912	2,171	1.0009	<0.0001
Pooled14	4.87935	2,165	1.0272	<0.0001
Pooled23	3.80673	949	1.0030	<0.0001
Pooled24	3.16119	943	1.3068	<0.0001
Pooled34	3.08766	942	1.0138	<0.0001

$$^1 y_i = \frac{x_i - 1}{w_i - 1} + b_7 \left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)} \right] + b_8 \left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)} \right]$$

where:

$$y_i = \frac{dob_{h_i}}{dbh_{ob}} \quad x_i = \frac{h_i}{h_t} \quad w_i = \frac{4.5}{h_t}$$

2

$$F_{\sum n_i - p, \sum (n_i - p)} = \left[\frac{Pooled SS_e}{\sum n_i - p} \right] \div \left[\frac{\sum SS_{e_i}}{\sum (n_i - p)} \right]$$

Table 4.—Mean percent differences (difference between felled-tree measurement and profile equation prediction as percent of felled-tree value - $\bar{d}$) and standard error of the mean percent difference ($s_{\bar{d}}$) for profile equation predictions of tree height and cubic foot volume from felled-tree and optical dendrometer data (Basis: 96 loblolly trees)

Profile value (mean of actual value)	Felled-tree		Criterion 400		Tele-Relaskop		Wheeler Pentaprism	
	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$
Height to 0 in. top (92.3 ft)	-0.002	0.002	+0.583	0.456	+1.684	0.781	+1.874	0.330
Height to 3 in. top (80.4 ft)	+1.873	0.355	+1.695	0.589	+3.401	0.794	+2.484	0.476
Height to 6 in. top (64.7 ft)	+3.400	1.410	-0.385	1.744	+5.318	1.463	-3.606	1.725
Height to 8 in. top (49.6 ft)	+4.805	1.800	+2.031	3.678	+9.439	2.158	-4.999	2.804
Height to 10 in. top (34.5 ft)	+6.212	2.848	-0.039	3.036	+11.236	3.025	-4.735	3.209
Volume to 0 in. top (49.4 ft ³)	+0.483	0.938	-3.027	1.305	+3.658	1.278	-7.031	1.252
Volume to 3 in. top (49.2 ft ³)	+0.496	0.966	-3.117	1.323	+3.663	1.295	-7.226	1.273
Volume to 6 in. top (47.3 ft ³)	+1.891	1.552	-3.594	2.101	+5.635	1.699	-10.379	1.956
Volume to 8 in. top (43.1 ft ³)	+2.315	1.734	-1.089	3.817	+8.728	2.211	-10.549	2.878
Volume to 10 in. top (36.4 ft ³)	+3.277	2.631	-3.217	3.225	+10.085	3.112	-9.782	3.249

DENDROMETER COMPARISONS

Point Estimates

The Criterion 400 was more accurate for dbh and total height measurement than the Tele-Relaskop or the Wheeler Pentaprism (table 1). Although the mean percent differences were significantly different statistically, they were most likely not different in a practical sense. The mean percent differences translated in absolute units to -0.05, +0.20, and -0.34 in. of the mean tree dbh for the Criterion 400, Tele-Relaskop, and Wheeler Pentaprism instruments, respectively. None of these mean differences would result in a change in tree diameter for a 1-in. dbh class interval.

The mean percent differences for a quadratic mean dob_{16} of 12.6 in. would translate, in absolute units, to -0.24, +0.19, and -0.52 in. for the Criterion 400, Tele-Relaskop, and Wheeler Pentaprism, respectively. Although these differences might appear to be insignificant from a practical standpoint, they could translate into significant volume differences if the dbh and dob_{16} dendrometer measurements were used to obtain Mesavage and Girard form class volumes (Mesavage and Girard 1946, Parker 1998). For example, using the average tree values of $dob_{16} = 12.6$ in. and $dbh_{ob} = 14.1$ in., Equation (7) for dbh_{16} , and Equation (9) for dib_{16} , the computed form class for the "average tree" would be:

$$\begin{aligned} dbh_{16} &= -0.3815 + 0.8896(14.1 \text{ in. } dbh_{ob}) \\ &= 12.16 \text{ in.} \quad \text{from Equation (7)} \end{aligned}$$

$$\begin{aligned} dib_{16} &= 12.6(12.16/14.10)\exp[0.0642(14.1/12.6 - 1)^{0.25}] \\ &= 11.29 \text{ in.} \quad \text{from Equation (9)} \end{aligned}$$

$$\begin{aligned} FC &= (11.29/14.10)100 \text{ percent} \quad \text{from definition of} \\ &= 80.04 \text{ percent} = 80 \text{ percent} \quad \text{form class} \end{aligned}$$

Likewise, using the resulting average dob_{16} values for the dendrometers (i.e., 12.6-0.24, 12.6+0.19, 12.6-0.52), the resulting dbh_{ob} values (i.e., 14.1-0.05, 14.1+0.20, 14.1-0.34), Equation (7) for dbh_{16} , and Equation (9) for dib_{16} , the computed form classes for the "average" Criterion 400, Tele-Relaskop, and Wheeler Pentaprism tree would be 79 percent, 80 percent, and 79 percent, respectively. If the assumption of 3 percent (bd ft) volume change per form class point is used, the volume differences would be -3 percent, 0 percent, and -3 percent, respectively. Cubic foot volume changes approximately 2 percent per form class point. Thus, the combined measurement data for dbh and dob_{16} indicate that the Tele-Relaskop would produce more reliable volume results than would the other instruments if the dendrometer measurements were used with form class volumes.

The results in table 1 indicate that the Criterion 400 was more accurate (in a practical sense, or showed less bias in a statistical sense) for total height measurement than was the Tele-Relaskop or the Wheeler Pentaprism. Again, the mean percent differences are not different from a practical standpoint because they translate to absolute height differences of 0.5, 1.6, and 1.7 ft from the average tree height of 92.8 ft. The height differences associated with the Wheeler Pentaprism are attributable to the accuracy of the attached clinometer, not the optics of the dendrometer.

Profile Equation Estimates

All upper stem profile equations (from Equation (4)) were judged to be statistically significant, and all possible pairwise comparisons showed that each equation was significantly different from the others at a significance probability of less than 0.0001 (table 3). The large degrees of freedom in the pooled comparisons forced all comparisons to be judged significantly different.

Because the primary objective of this study was to compare volume prediction accuracy of stem profile equations developed from optical dendrometer and felled-tree data, estimates of merchantable height (i.e., stem length) and cubic foot volume to various top merchantability limits were computed with the profile equations for each data set and compared to the felled-tree values (table 4). The ob upper stem profile equation coefficients for each data set (b_7 and b_8 in table 2) were used to compute estimates of merchantable height and volume above breast height. Cubic foot volume below breast height was computed for all data sets with predicted diameters at 0.5 and 3.0 ft from felled-tree Equations (6) and (8), respectively. Profile equations for predicting diameters below breast height were not developed for the dendrometers because in field applications, visibility of the stump and most stem locations below breast height is severely limited by forest vegetation. This is not a serious limiting factor in dendrometer use because the stem section below breast height can be treated as a cylinder or other appropriate geometric solid.

The accuracy of computed height (stem length) and volume values to a specified merchantability limit from a felled-tree profile equation diminishes as the merchantability limit moves down the stem from the top toward breast height (table 4). This decline in prediction accuracy is attributable in part to changes in taper caused by inflection points of the stem profile. The upper stem profile equations used in this study are constrained through the top and breast height, but as the rate of stem taper decreases in the mid-portion of the tree bole above breast height, relatively small changes in predicted diameter result in large changes in stem length (height). For example, the mean measured felled-tree heights in

table 4 reflect a taper rate of 0.252 in./ft between the tree top and a 3-in. top dbh, 0.191 in./ft between 3 in. and 6 in., 0.132 in./ft between 6 in. and 8 in., 0.132 in./ft between 8 in. and 10 in., and 0.134 in./ft between 10 in. and the average dbh of 14.1 in. These "average tree" taper rates show that the stem profile is "relatively flat" (actually, the taper rate is relatively constant) between a 6-in. top and dbh. Thus, a +4.8 percent error in height to an 8-in. top translates to +2.4 ft, which equates to a error of +0.295 in. in diameter prediction if the taper rate is 0.132 in./ft. From a practical standpoint, a 4-6 percent error in merchantable height prediction in the mid-bole region of a standing tree should have little impact on volume prediction.

The error associated with profile equation prediction of merchantable height (table 4) increases in a consistent manner as the top merchantability limit increases (i.e., moves down the stem toward dbh) for the felled-tree and Tele-Relaskop data sets, appears to be random for the Criterion 400 data, and has a segmented trend for the Wheeler data.

Errors in profile prediction of cubic foot volume should be attributable to the combined effects of errors in merchantable height and stem diameter prediction. For example in table 4, the average height prediction error (expressed as mean percent difference) for the felled-tree data profile equation is +4.805 percent or 2.38 ft for the 8-in. top. Using the previously established taper rate of 0.132 in./ft, the end diameter of this +2.38 ft "error bolt" would be approximately 8.3 in. and its cubic foot volume would be approximately +0.86 ft³. The actual volume difference for the 8-in. top in table 4 is +2.315 percent or 0.99 ft³.

Overestimation of height and/or stem diameter should result in overestimation of cubic foot volume. The computed values for felled-tree and Tele-Relaskop equations produced consistent error patterns in diameter, height, and cubic foot volume. The Tele-Relaskop overestimated dbh, dob₁₆, and total tree height (table 1), and the resulting profile equations overestimated merchantable height and therefore cubic foot volume (table 4). The Criterion 400 underestimated standing tree diameters, overestimated total height, and had both positive and negative estimation errors in profile height prediction. Yet, the profile equation volume prediction was consistently low. Because cubic foot volume varies with the square of bolt diameter, it must be concluded that the Criterion 400's underestimation of stem diameter has a stronger influence on volume prediction than does its inconsistent estimation of height. Likewise, the Wheeler Pentaprism underestimated standing tree diameters and the resulting profile equations consistently underestimated cubic volume by 7.0 to 10.5 percent.

It is obvious that profile equations developed with felled-tree data produce the most consistent estimates of merchantable height and cubic foot volume to various merchantable top limits. It is difficult, however, to make definitive conclusions about the accuracy ranking of the Criterion 400, Tele-Relaskop, and Wheeler Pentaprism. In general, the Criterion 400 produced the smallest mean differences in standing tree measurements and profile equation predictions of merchantable height and cubic foot volume. On the other hand, the Tele-Relaskop produced the most consistent tree measurement and profile prediction trends. There is no doubt that the Wheeler Pentaprism was the least accurate of the three dendrometers in a statistical sense, but these inaccuracies may not be relevant in a practical sense.

LIMITATIONS AND RECOMMENDATIONS

The results of this study indicate that the Criterion 400 is slightly more accurate for measurement of tree diameters and heights than the Tele-Relaskop. It is approximately 50 percent more costly than the Tele-Relaskop and has both advantages and limitations for forestry applications. The primary advantage of the Criterion 400 is its surveying and distance measuring capabilities. Its most serious limitations include laser deflection on brush and tree foliage between the instrument and the target stem location, and poor light quality and graduation intervals on the scope recticle for diameter measurement. Laser deflection becomes extremely critical when measuring stem diameter because diameter is directly proportional to the true horizontal distance to the target tree and inversely proportional to the product of the graduation interval on the scope recticle and the cosine of the vertical angle to the stem measurement point. An erroneous target distance and/or resultant diameter reading are the only clues to indicate deflection and the user must judge the relevance of the acquired measures. This limitation can be overcome with a target reflector and an electronic filter to discriminate between light reflected from the target reflector and vegetation (Carr 1996).

The graduation intervals on the scope recticle are difficult to see against some background conditions and difficult to read because of the uniform black graduations. The user must be continually aware of the resulting diameter and height measure so that another measurement can be taken if the measure(s) seem out of range. Tree diameters would be much easier to measure if the scope recticle graduations had contrasting tic marks: some oriented up and some oriented down from the primary horizontal line. A variable power scope would also improve the visual capabilities.

The Tele-Relaskop has relatively good internal light qualities, and its 8X magnification allows the user to see

the tree stem against various background lighting conditions. The alternating black and white horizontal graduations are easy to see, but the user must be extremely careful in aligning the left side of a white-black graduation unit (1 percent) on the outer edge of the stem and reading the "vernier" on the right side to the nearest 0.01 percentage unit (Parker 1997). The vertical scale must be read to the nearest 1/4 to 1/2 percentage unit for upper stem measurements. Because stem diameter and height measurements are obtained in relative percentage units of the horizontal instrument distance from the tree and the horizontal distance is determined from measured dbh, measurement of dbh with a diameter tape versus a caliper will produce different upper stem values. Measurement of dbh with a caliper is highly recommended.

Both the Criterion 400 and Tele-Relaskop must be used with a sturdy tripod that has head leveling capabilities. A good quality, lightweight photographic tripod can be used with the Tele-Relaskop. Future enhancements to the Criterion 400 will hopefully reduce the weight and bulk of the necessary battery packs and large surveying-type tripod.

When measuring upper stem heights and diameters with either instrument, the user must be at a horizontal distance equal to 1.0 to 1.5 times the tree height on flat terrain or not exceed a 45° above or below the horizontal on steep terrain. Both the Criterion 400 and the Tele-Relaskop have maximum angle limitations of approximately 60°. The Criterion 400 will emit a beep if the maximum angle is exceeded. The Tele-Relaskop has no such warning and erroneous readings are possible.

The surveying and tree measurement capabilities of the Criterion 400 make it a more versatile instrument than the Tele-Relaskop, but potential users should evaluate each instrument on the basis of their requirements and intended usage.

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