Five Instruments for Measuring Tree Height: An Evaluation

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ABSTRACT. *Five instruments were tested for reliability in measuring tree heights under realistic conditions. Four linear models were used to determine if tree height can be measured unbiasedly over all tree sizes and if any of the instruments were more efficient in estimating tree height. The laser height finder was the only instrument to produce unbiased estimates of the true height for all four linear models. An accuracy test showed the clinometer and enbeeco instruments produced biased results in the 0–33 and > 66 ft height classes respectively. The results for the laser may be misleading due to the limited amount of data collected with this instrument. The results (subjectively) confirm that trees up to 40 ft are measured very accurately with no exceptions for the clinometer, relaskop, and enbeeco. The tele-relaskop generally produced results that were poorer than the other instruments. South. J. Appl. For. 18(2):76–82.*

When measuring the height of a tree, where the base and top are well defined and clearly visible, the existing instruments for measuring the height of standing trees are adequate for most applications (Hunt 1958, Warren 1959, Rennie 1979). However, the variance and bias of the height estimates could be large for tall trees in dense stands or for trees which do not have well-defined tops. An opportunity to evaluate some of the currently available height measurement instruments (including a laser-driven instrument) presented itself in the summer of 1991. Tree climbers, who were employed to collect foliage samples for chemical analysis, measured the true height of standing trees. Readings from a number of different height measuring instruments were compared to the values obtained by the tree climbers. These data were used to determine if any one instrument was superior to the other instruments under real world conditions.

Data Description and Collection Methods

The data set consists of 100 hardwood and softwood trees with 21 different species. The predominant species are loblolly (*Pinus taeda* L.), slash (*Pinus elliottii* Engelm. var. *elliottii*), shortleaf (*Pinus echinata* Mill.) and longleaf pine (*Pinus Palustris* Mill.). Seventeen additional species including a variety of oaks also appear in the data set.

All data collected are from Forest Health Monitoring plots in Georgia. True heights for all trees were taken while crews collected foliage samples from the tree crowns. One crew member climbed as high as possible up each tree. From that point poles were used to measure the remaining distance to the top of the tree. To determine when the pole was at the top of the tree, sightings were taken from the ground by two observers and by the crew member in the tree. When all crew members were in agreement, the total height from the ground to the top of the pole was calculated. While some measurement error exists in this method, no alternative method could be implemented which met time and cost constraints and still represented realistic measurement situations, such as varying terrain, canopy, tree height distributions, and species mix

Readings from a laser height finder (Jasumback 1991), Suunto clinometer (Husch et al. 1982), Speigel relaskop, Enbeeco clinometer[1], Speigel tele-relaskop (Bitterlich 1978, Husch et al. 1982) were recorded from the same location. All measurements were taken by an experienced field crew member. A tripod was used to steady each instrument. This required adapting a tripod mount for the Suunto clinometer,

NOTE: Mention of trade names or commercial products does not constitute endorsement or recommendation of use.

[1] H. Steward Ltd, Enbeeco House, Carlton Park, Saxmundham, Suffolk IP17 2NL, U.K.

which is designed to be hand held. All other instruments had thumb screw systems to accommodate tripods. The laser height finder was a preproduction model and was not available until late in the field season. Sample sizes with this instrument were smaller than the other four instruments due to the limited amount of time it was available for testing.

The instruments were set up at a distance from the tree so that a 45° measurement angle was never exceeded. The measurements were taken from the uphill side of each tree provided an open line of sight to the top of the tree could be found. For two trees in the data set, measurements could not be taken from an uphill position.

A combination of scales was used so that no two instruments successively utilized the same scale. The Suunto clinometer and the enbeeco used the percent scale, the relaskop used the topographic scale, and the tele-relaskop and the laser height finder used the degree scales.[2] This provided a quasi "blind" aspect to the study, intended to interrupt the tendency to "drive" the current readings to be the same as those obtained with the previous instrument. Distances from the observer to the tree in the data set were given as slope distances. Level distances were computed for the analysis.

Evaluation Techniques

Four linear models were fit to the data to test the bias and efficiency of the height measurements and to determine if there is an upper limit to the reliability of the instruments. Ideally, the correlation between true height and measured height would be 1, thus the first model was specified as

$$h_t = \beta h_m + \varepsilon \qquad (1)$$

where h_t is the true height and h_m is the measured height. The error terms, ε, are assumed to be normally distributed with mean 0 and variance σ^2.

The assumption of equal variance in the error term is highly suspect. A reasonable assumption is that the error in measurement increases proportionally with tree height. Therefore the model

$$e^{h_t} = e^{\beta h_m} + \varepsilon_1 \qquad (2)$$

was fit to remove the effect of the heteroscedasticity. An intercept term was added to (1), yielding

$$h_t = \alpha + \beta h_m + \varepsilon \qquad (3)$$

The error terms, ε, are assumed normally distributed with mean 0 and variance σ^2. An intercept was also fit to the log transformed data, yielding

$$e^{h_t} = e^{\alpha + \beta h_m} + \varepsilon_1 \qquad (4)$$

R^2 values were used for an indicator of goodness of fit. Larger R^2 values indicated a better agreement between the estimated and actual heights. For this study, R^2 was defined as

$$R^2 = 1 - \frac{SSE}{SST}$$

where

$$SSE = \sum_{i=1}^{n} (h_{t_i} - \hat{h}_{m_i})^2$$

$$SST = \sum_{i=1}^{n} (h_{t_i} - \bar{h})^2$$

$\hat{h}_{m_i}$ is the estimated height generated from the four models

h_{t_i} is the true height and h is the mean of the true heights.

Confidence intervals for models (1) and (2) allowed the hypothesis

$$H_0: \beta = 1$$

to be tested. Analysis of β for models (1) and (2) was used to test if a bias in estimation exists for any of the instruments. For models (3) and (4) the hypothesis

$$H_0: \alpha = 0, \beta = 1$$

was tested.

The four models were fit for two sets of data. First for all species of trees together, then for softwood trees only. Hardwoods were removed to examine the effect of extracting additional variability caused by poorly defined central stems typical of many hardwood species.

In addition to the linear model comparison, an accuracy test based on both bias and precision was used (Reynolds 1984). Mean error was used as a measure of bias. Then confidence intervals were generated about the mean error. The bias is considered significant if the confidence interval does not contain zero. The confidence interval were generated using

$$\bar{e} \pm \frac{S t_{1-\frac{\alpha}{2}, n-1}}{\sqrt{n}}$$

where

[2] Husch et al. (1982) give a full description of the different scales used.

$$\bar{e} = \sum_{i=1}^{n} \frac{\hat{h}_{m_i} - h_{m_i}}{n}$$

$$S = \sqrt{\sum_{i=1}^{n} \frac{(e_i - \bar{e})^2}{n-1}}$$

$t_{1-\frac{\alpha}{2},n-1}$ = Student' s t distribution at 1 - a /2 with

n - 1 degrees of freedom

n = number of observations

This test requires a homogeneous error structure, which is not present in the data. Therefore the data set was divided into three height classes to obtain roughly homogeneous variances within each height class. The height classes chosen were 0–33, 33–66 and >66 ft. The accuracy test was performed on the data set containing all trees and the data set with the hardwood trees removed.

To determine if there is a specific tree height at which instrument measurements are no longer accurate, a visual comparison of model errors was performed. The visual comparison entailed graphing the measured height versus true height and looking for a point in the scatter plot where the errors in measurement increased drastically. As an example, Figure 1 shows the relationship between true height and measured height using the clinometer. Both hardwood and softwoods are plotted and can be differentiated by the symbols used.

A comparison of model errors was performed by computing the average absolute error between the model (1) estimates and the true heights by 10 ft height classes. These values were computed using the formula

$$\sum_{i=1}^{n_h} \frac{|\beta h_m - h_t|}{n_h}$$

where n_h is the number of trees in a given height class. Average errors in each height class provided a good indicator of how accurately tree growth can be measured for a given height with each of the instruments.

Results and Discussion

Tables 1–4 give results for fitting the four models to the data set with all species and the data set with only softwood trees. The accuracy test results by height class are given in Tables 5 and 6. The average absolute errors by height class are given in Tables 7 and 8.

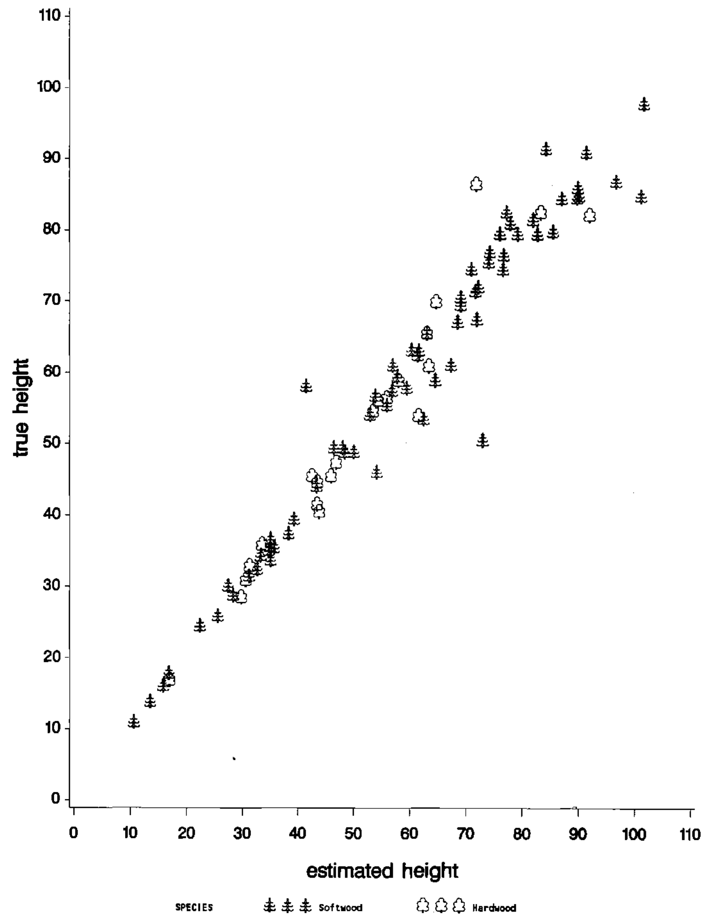

Figure 1.

For the clinometer the models without intercept terms [models (1) and (2)] had confidence intervals containing β = 1 , regardless of whether all species or only softwood species were considered. In contrast, for models with intercept terms ([models (3) and (4)], no confidence interval contained either $\alpha = 0$ or $\beta = 1$. R^2 values ranged from 0.9462 to 0.9739. When all species were considered the R^2 values were consistently second largest compared to the other four instruments. When only softwood trees were considered the R^2 values were third largest, regardless of whether the data was transformed or which model was fit. For the accuracy test the clinometer showed a significant bias in the 0–33 ft height class. In the other two height classes, the bias was nonsignificant.

The results for the relaskop were similar to those for the clinometer. For the models without intercept terms [models (1) and (2)] the confidence intervals for β contained 1. When the intercept term was added ([models (3) and (4)], the confidence intervals contained $\alpha = 0$ and $\beta = 1$ for both of the log transformed data sets. This may imply that the errors in fit occurred because of heteroscedasticity in the data. R^2 values ranged from 0.9363 to 0.9704. For the relaskop the R^2 values were always third largest for the all species data sets and R^2 values were fourth largest when only softwood trees were included in the data set.

For the tele-relaskop the confidence intervals contain β = 1 for the models without intercept terms. When intercept terms were added, the confidence intervals contained $\alpha = 0$ and $\beta = 1$ for the untransformed data using both the all-

Table 1. Regression coefficients, standard errors, 95% confidence intervals, and R^2 values with the untransformed data and all trees.

Instrument	Model #	Parameter	Estimate	Std. Err.	CI	R^2	n
Clinometer	[1]	β	0.9888	0.0084	(0.9720, 1.0056)*	0.9462	90
	[3]	α	3.6659	1.3941	(0.8954, 6.4364)	0.9501	
	[3]	β	0.9329	0.0228	(0.8876, 0.9781)		
Relaskop	[1]	β	0.9835	0.0090	(0.9655, 1.0016)*	0.9372	90
	[3]	α	3.6330	1.5225	(0.6074, 6.6586)	0.9410	
	[3]	β	0.9283	0.0248	(0.8791, 0.9776)		
Tele-relaskop	[1]	β	0.9950	0.0160	(0.9628, 1.0272)*	0.8990	51
	[3]	α	4.4237	2.5880	(-0.7771, 9.6245)*	0.9047	
	[3]	β	0.9266	0.0430	(0.8403, 1.0130)		
Enbeeco	[1]	β	0.9746	0.0088	(0.9570, 0.9921)*	0.9505	76
	[3]	α	3.3680	1.5062	(0.3666, 6.3693)	0.9537	
	[3]	β	0.8835	0.0372	(0.8093, 0.9576)		
Laser	[1]	β	1.0008	0.01858	(0.9609, 1.0406)*	0.9250	15
	[3]	α	4.4341	4.9531	(-6.2665, 15.1346)*	0.9293	
	[3]	β	0.9387	0.0718	(0.7836, 1.0938)		

* Indicates unbiased fit.

species data set and the softwoods-only data set. Using R^2 values as an indication of fit, the tele-relaskop produced the worst fit for all models and data sets considered.

The enbeeco was the only instrument which did not have confidence intervals containing $\beta = 1$ for all models without intercept terms. When model (1) was fit to the softwood data the assumption that $h_t = h_m$ was rejected. When intercept terms were added, model (4) had confidence intervals containing $\alpha = 0$ and $\beta = 1$ for the softwood data. R^2 values for the enbeeco were consistently the largest when all tree species were considered. When only softwood trees were considered, the R^2 value for models (1), (3) and (4) were the second largest among all instruments and largest when model (2) was fit.

Table 2. Regression coefficients, standard errors, 95% confidence intervals, and R^2 values for log transformed data and all trees.

Instrument	Model #	Parameter	Estimate	Std. Err.	CI	R^2	n
Clinometer	[2]	β	1.0003	0.0021	(0.9961,1.0045)*	0.9702	90
	[4]	α	0.2074	0.0669	(0.0745, 0.3403)	0.9731	
	[4]	β	0.9485	0.0168	(0.9151, 0.9819)		
Relaskop	[2]	β	0.9984	0.0021	(0.9942,1.0027)*	0.9687	90
	[4]	α	0.1228	0.0727	(-0.0216,0.2673)*	0.9697	
	[4]	β	0.9678	0.0182	(0.9316, 1.0041)		
Tele-relaskop	[2]	β	1.0024	0.0048	(0.9926,1.0120)*	0.9215	51
	[4]	α	0.3822	0.1312	(0.1046, 0.6599)	0.9321	
	[4]	β	0.9065	0.0349	(0.8362, 0.9767)		
Enbeeco	[2]	β	0.9963	0.0023	(0.9918,1.0008)*	0.9726	76
	[4]	α	0.1375	0.0735	(-0.0090, 0.2839)	0.9735	
	[4]	β	0.9623	0.0183	(0.9257, 0.9988)		
Laser	[2]	β	1.0017	0.0041	(0.993,1.010)*	0.9597	15
	[4]	α	0.2665	0.2086	(-0.1842,0.7172)*	0.9642	
	[4]	β	0.9380	0.0501	(0.8297, 1.0462)		

* Indicates unbiased fit.

Table 3. Regression coefficients, standard errors, 95% confidence intervals, and R^2 values for untransformed data with all hardwood trees removed.

Instrument	Model #	Parameter	Estimate	Std. Err.	CI	R^2	n
Clinometer	[1]	β	0.9846	0.0096	(0.9655, 1.0037)*	0.9480	68
	[3]	α	3 9622	1.6137	(0.7403, 7.1841)	0.9523	
	[3]	β	0.9262	0.0255	(0.8753, 0.9771)		
Relaskop	[1]	β	0.9837	0.0106	(0.9625, 1.0048)*	0.9363	68
	[3]	α	4.1243	1.8004	(0.5297, 7.7189)	0.9410	
	[3]	β	0.9229	0.0284	(0.8661, 0.9797)		
Tele-relaskop	[1]	β	0.9983	0.0195	(0.9589, 1.0377)*	0.8961	41
	[3]	α	4.3524	3.1092	(-1.9418, 10.6467)*	0.9012	
	[3]	β	0.9335	0.0501	(0.8320, 1.0350)		
Enbeeco	[1]	β	0.9707	0.0098	(0.9511, 0.9903)	0.9535	59
	[3]	α	3.6061	1.7017	(0.1984, 7.0138)	0.9569	
	[3]	β	0.9197	0.0258	(0.8679, 0.9715)		
Laser	[1]	β	0.9899	0.0171	(0.9517, 1.0284)*	0.9542	11
	[1]	α	5.1553	4.3162	(-4.6086, 14.9192)*	0.9605	
	[3]	β	0.9185	0.0621	(0.7780, 1.0589)		

* Indicates unbiased fit.

Table 4. Regression coefficients, standard errors, 95% confidence intervals, and R^2 values for log transformed data with all hardwood trees removed.

Instrument	Model #	Parameter	Estimate	Std. Err.	CI	R^2	n
Clinometer	[2]	β	0.9996	0.0025	(0.9946, 1.0047)*	0.9702	68
	[4]	α	0.2321	0.0761	(0.0802, 0.3842)	0.9739	
	[4]	β	0.9421	0.0190	(0.9042, 0.9801)		
Relaskop	[2]	β	0.9989	0.0025	(0.9938, 1.0040)*	0.9694	68
	[4]	α	0.1242	0.0834	(-0.0422, 0.2907)*	0.9704	
	[4]	β	0.9681	0.0208	(0.9266, 1.0097)		
Tele-relaskop	[2]	β	1.0031	0.0060	(0.9911, 1.0152)*	0.9220	40
	[4]	α	0.3595	0.1596	(0.0364, 0.6827)	0.9312	
	[4]	β	0.9133	0.0403	(0.8318, 0.9949)		
Enbeeco	[2]	β	0.9956	0.0026	(0.9904, 1.0009)*	0.9743	59
	[4]	α	0.1370	0.0815	(-0.0262, 0.3002)*	0.9755	
	[4]	β	0.9620	0.0202	(0.9220, 1.0024)		
Laser	[2]	β	1.0000	0.0042	(0.9907, 1.0092)(	0.9730	n=11
	[4]	α	0.3349	0.1800	(-0.0723, 0.7421)*	0.9805	
	[4]	β	0.9199	0.0432	(0.8221, 1.0177)		

* Indicates unbiased fit.

Table 5. Confidence intervals for accuracy test and number of trees in each of the three height classes for all trees.

Height class	Clinometer	Relaskop	Tele-relaskop	Enbeeco	Laser
0–33	(-1.28, -0.12), 13	(-0.62, 0.64), 13	(-2.43, 0.51), 7	(-0.95, 0.67), 10	*
33–66	(-1.45, 1.66), 45	(-1.08, 1.74), 45	(-2.71, 3.71), 26	(-1.03, 2.71), 35	(-2.08, 0.68), 5
> 66	(-1.42, 2.63), 32	(-1.68, 3.46), 32	(-4.51, 2.05), 18	(-0.25, 3.66), 31	(-4.88, 5.02), 9

* Indicates not enough data to calculate confidence interval.

Table 6 Confidence intervals for accuracy test and number of trees in each of the three height classes with all hardwood trees removed.

Height class	Clinometer	Relaskop	Tele-relaskop	Enbeeco	Laser
0–33	(-1.58-0.31), 10	(-0.85 0.79), 10	(-2.43 0.51), 7	(-1.09 0.76), 9	*
33–66	(-1.89 2.64), 30	(-1.81 2.15), 30	(-4.14 5.80), 17	(-1.97 3.75), 22	(-3.45 0.72), 3
> 66	(-0.83 2.90), 28	(-1.62 3.69), 28	(-4.95 1.95), 17	(0.51 4.15), 28	(-2.98 5.79), 7

* Indicates not enough data to calculate confidence interval.

Table 7. Average absolute model deviation and number of trees in each 10 ft height class for all trees. The model used is $h_t = \beta h_m$ (1).

Height class	Clinometer	Relaskop	Tele-relaskop	Enbeeco	Laser
10–20	0.80, 5	0.71, 5	2.05, 3	0.61, 5	
20–30	1.20, 4	0.42, 4	0.50, 3	1.35, 3	
30–40	1.33, 14	1.15, 14	3.94, 8	1.51, 11	1.37, 2
40–50	2.22, 12	1.76, 12	4.56, 7	2.51, 10	0.03, 1
50–60	5.09, 15	4.18, 15	6.03, 9	5.34, 11	0.64, 1
60–70	2.89, 11	2.12, 11	2.66, 6	2.06, 9	3.38, 3
70–80	2.69, 13	3.23, 13	3.37, 8	1.97, 13	3.32, 4
80–90	5.86, 13	6.96, 13	3.01, 5	5.16, 12	6.45, 4
90–100	3.84, 3	7.98, 3	11.31, 3	5.44, 3	

Table 8. Average absolute model deviation and number of trees in each 10 ft height class with all hardwood trees removed. The model used is $h_t = \beta h_m$ (1).

Height class	Clinometer	Relaskop	Tele-relaskop	Enbeeco	Laser
10–20	0.97, 4	0.70, 4	2.02, 3	0.65, 4	
20–30	1.46, 3	0.39, 3	0.48, 3	1.45, 3	
30–40	1.24, 11	0.93, 11	4.78, 6	1.33, 9	1.71, 2
40–50	2.74, 6	1.25, 6	6.78, 4	3.21, 4	
50–60	6.24, 10	4.98, 10	8.77, 5	7.48, 6	
60–70	3.07, 9	2.25, 9	2.40, 5	2.29, 8	3.56, 3
70–80	2.60, 12	3.04, 12	3.39, 7	1.65, 12	3.30, 4
80–90	5.02, 10	6.46, 10	3.08, 5	4.49, 10	4.44, 2
90–100	3.94, 3	8.00, 3	11.26, 3	5.29, 3	

The laser height finder has the distinction of being the only instrument whose confidence intervals contained $\beta = 1$ and $\alpha = 0$ under every model and data set. The R^2 values were fourth largest when all species were considered. R^2 values were the largest for the softwood data except when model (2) was fit. In that case the R^2 value was second largest.

For the accuracy test the clinometer was the only instrument to show a significant bias using the data set which included all trees. The significant bias was in the 0–33 ft height class. In the 33–66 and >66 ft height classes the bias was nonsignificant for every instrument. When the hardwood trees were removed from the data set the clinometer still showed a significant bias in the 0–33 foot class. The Enbeeco also showed a significant bias in the >66 ft height class. There was only one tree less than 33 ft tall measured with the laser so no accuracy test could be performed in this height class.

The analysis of the absolute average error by diameter class is given in Tables 7 and 8. In all height classes less than 40 ft the average absolute errors were generally less than 1.5 ft with the exception of the tele-relaskop, which had error values in the 40-ft class of 3.94 and 4.78 for the all-species and softwood-only data sets, respectively. For trees greater than 40 ft tall, the error values increase. The error values range from 0.03 to 11.31 ft with most values falling in the 2 to 5 ft range. In most cases removing the hardwood trees from the data reduced the average absolute error. The clinometer, relaskop, Enbeeco, and laser height finder produced similar results in all height classes. The tele-relaskop produced larger errors in the 30–60 and 90–100 foot height classes.

The graphical analysis also subjectively confirms that trees less than 40 ft are measured accurately. No substantial disagreements between measured and true height are seen in the data until after the 40 ft level. As height increases, the graphs indicate an increasing disagreement between true and measured height.

Conclusions

Results using the four linear models and average error tests were similar for the clinometer, relaskop, and Enbeeco instruments. Both the clinometer and Enbeeco showed significant biases in the 0–33 and >66 ft height classes. The tele-relaskop appeared to be slightly less accurate. Even though the results for the laser would indicate that it is the least likely to produce biased estimates, the effectiveness of this instrument is still difficult to determine because of the limited amount of data available. In addition, the laser height finder used in this study was an early preproduction model. Numerous design improvements have been made on current models, which may improve accuracy. Additional testing with the laser height finder would be prudent. The graphical and average error analysis indicates that trees less than 40 ft tall can be measured quite accurately. If errors of 2 to 5 ft can be tolerated, all of the instruments, except the tele-relaskop, are suitable for measuring trees less than 40 ft tall.

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