Southern Cross University
ePublications@SCU

School of Environment, Science and Engineering Papers

School of Environment, Science and Engineering

1998

Accuracy and precision of two laser dendrometers

J P. Skovsgaard
University of Copenhagen

V K. Johannsen
Danish Forest & Landscape Institute

Jerome K. Vanclay
Southern Cross University

Publication details

Post-print of Skovsgaard, JP, Johannsen, VK & Vanclay, JK 1998, 'Accuracy and precision of two laser dendrometers', *Forestry*, vol. 71, no. 2, pp. 131-139.
This is a pre-copy-editing, author-produced PDF of an article accepted for publication in Forestry following peer review. The definitive publisher-authenticated version is available online at: http://dx.doi.org/10.1093/forestry/71.2.131

ePublications@SCU is an electronic repository administered by Southern Cross University Library. Its goal is to capture and preserve the intellectual output of Southern Cross University authors and researchers, and to increase visibility and impact through open access to researchers around the world. For further information please contact epubs@scu.edu.au.

Postprint of: *Forestry* **71**(2):131-139.

Accuracy and precision of two laser dendrometers

J. P. SKOVSGAARD[1], V. K. JOHANNSEN[1] and J. K. VANCLAY[2]*

[1] Danish Forest and Landscape Research Institute, Horsholm Kongevej 11, DK-2970 Horsholm, Denmark
[2] Royal Veterinary and Agricultural University, Thorvaldsensvej 57, DK-1871 Frederiksberg, Denmark
* Present address: CIFOR, PO Box 6596 JKPWB, Jakarta, Indonesia.

Summary

Two commercial laser dendrometers were tested under controlled and field conditions, and contrasted with alternative instruments. Testing focused on height measurement, but also considered distance and remote diameter measurements. Both laser instruments gave very precise estimates, but showed some bias. Users of these and other `high-tech' instruments are reminded that precision is not synonymous with accuracy. Users should not become complacent about the sub-millimetre readout, but should calibrate instruments to examine if users' accuracy requirements are satisfied. Instruments may need to be re-calibrated each measurement season and after any mishandling.

Introduction

Laser dendrometers first became commercially available in 1991 (e.g. Jasumback and Carr, 1991; Carr, 1993), but have quickly gained acceptance and now there are some hundreds of instruments in service. Two manufacturers, Laser Technology Inc. (Denver, USA) and Jenoptik (Jena, Germany), presently dominate, but laser hypsometers are also available from other suppliers (e.g. Easy Ranger, South Africa). Here we are concerned with laser dendrometers, but other electronic instruments are also available (e.g. the acoustic hypsometer from Forestor Instrument AB, Taby, Sweden, see Jonsson *et al.,* 1992). Although these instruments are expensive compared with traditional analogue hypsometers, they offer considerable potential to improve the efficiency of forest surveys. Here we report parts of an evaluation of two laser dendrometers to examine their suitability for use in practical forestry applications. Both instruments have a digital display able to show many digits, giving the impression of great accuracy. Both have good precision and different operators may obtain very similar results under controlled conditions. However, it is dangerous to assume that precision implies accuracy, and our evaluation was concerned largely with detecting any possible bias in these instruments.

Despite a statistically based experimental design we adopt a narrative style rather than the traditional Materials-Methods-ResultsDiscussion pro forma, because our evaluation evolved substantially as we became more aware of capabilities and limitations of the instruments. This progressive modification of our trial offered better insights into the performance of the instruments, but confounded some factors in the trial and so hampered analyses and interpretation. As with much new technology, there is a steep learning curve, and it was only after we completed our evaluation that we felt qualified to begin. Despite some weaknesses in our evaluation, we report our experience so that this and other evaluations (e.g. Liu *et al., 1993;* Duran, 1994; Fairweather, 1994; Williams *et al.,* 1994; Liu, 1995; see also grey literature cited by Carr, 1993) may help others choose an instrument or adjust mensuration procedures.

The instruments

We tested two laser dendrometers, the Jenoptik LEM 300-W/Forst and the Laser Technology Criterion 400, contrasting these with two analogue hypsometers. The laser instruments have similar specifications (see Table 1), but differ in styling. The German LEM (Laser-Entfernungs-Messgerat) is styled like binoculars, while the American Criterion is styled like a rifle with a telescopic sight. Both instruments can be used, and were tested, with and without a tripod.

We compared these with the JAL and Suunto hypsometers. The JAL hypsometer (J.A. Lovengreen, 1952; Anon., 1954) is regarded as one of the most accurate geometric hypsometers (Lovengreen, 1952; Schmid *et al.,* 1971; Loetsch *et al.,* 1973 p. 121; see, however, Olsen, 1968). Height estimates are based on geometrical inference (i.e. similar triangles) from a calibrated stave placed at the base of the target, so that the JAL does not involve measuring the horizontal distance to the target. We also included the Suunto because it is widely used and relies on trigonometry (i.e. measuring angles to the base and top of the target and using an independent estimate of horizontal distance, e.g. Schreuder *et al.,* 1993 p. 238). The Suunto (model PM 5/360PC, using the percentage scale) was hand-held, while the JAL hypsometer was used with a bipod (i.e. a two-legged support, cf. tripod).

After some informal tests of the LEM dendrometer in an urban situation, we devised a formal height measurement trial under both controlled and field conditions. The tests were completed under cold, slightly overcast conditions typical of field conditions during the field measurement season (winter). The LEM was tested in March 1993 (as was the controlled test with the JAL), while other testing was completed in January 1994 (2-3 days each). Participants were familiar with the JAL and Suunto hypsometers, but were new to the LEM and the Criterion.

Table 1: Selected specifications of laser dendrometers (various sources). Specifications may vary with model and manufacture date

Instrument	Jenoptik LEM 300-W	Laser Technology Criterion *400*
Mass (kg)	2.20	2.77
Dimensions (mm)		89 × 165 × 216
Range (to tree, m)	?-100	1.5-450
(to reflector, m)	-3000	-12000
Approx. price (£)	6,000	6,000
Accuracy claimed		
beam divergence (mrad)	1.2	3
distance (m)	0.1	0.1
inclination (°)	0.1	0.2
height (m)		0.15
direction (°)	NA	0.3
diameter (cm)		5

NA indicates a capability not available with the particular instrument.

Height measurement under controlled conditions

For the controlled test, we placed targets at three levels (approx. 10 m, *20* m, and *30* m, each with an offset known only to one of the authors, so that the actual heights were *9.8* m, *20.1* m and *29.9* m) up the wall of a five-storey concrete building at the Royal Veterinary and Agricultural University, and made reference marks representing distances equal to *75* per cent, 100 per cent, 150 per cent and 200 per cent of each of these levels in a paved car park adjacent to the building. In March 1993*,* each of three operators (skilled field staff) made five height measurements from each of the four reference distances, using the LEM both with and

without a tripod. Similar measurements were made with the JAL hypsometer (four operators). In January *1994,* the trial was repeated for the Criterion and Suunto hypsometers by the three authors. We had intended to use the original three operators, but other commitments precluded further input on their part. This means that the results are confounded, and that it is uncertain if differences are due to the instruments or to the operators.

Results suggested a bias in both the LEM and JAL instruments (Figure 1). Note that Figure 1 illustrates the residual e = y – y^ (the height determined by direct measurement with a steel tape minus the estimate obtained by remote measurement with hypsometer), and that a negative residual indicates an overestimate. Each datum is the mean of five observations. Estimates obtained with the JAL were consistently *1-2* per cent below the true values. The LEM performed best (with a 1 per cent overestimate) when used with a tripod and a sighting angle of *4S°*. It seems unlikely that lack of familiarity with the LEM could have influenced results in any significant way (i.e. compare tripod versus hand-held measurements with the LEM).

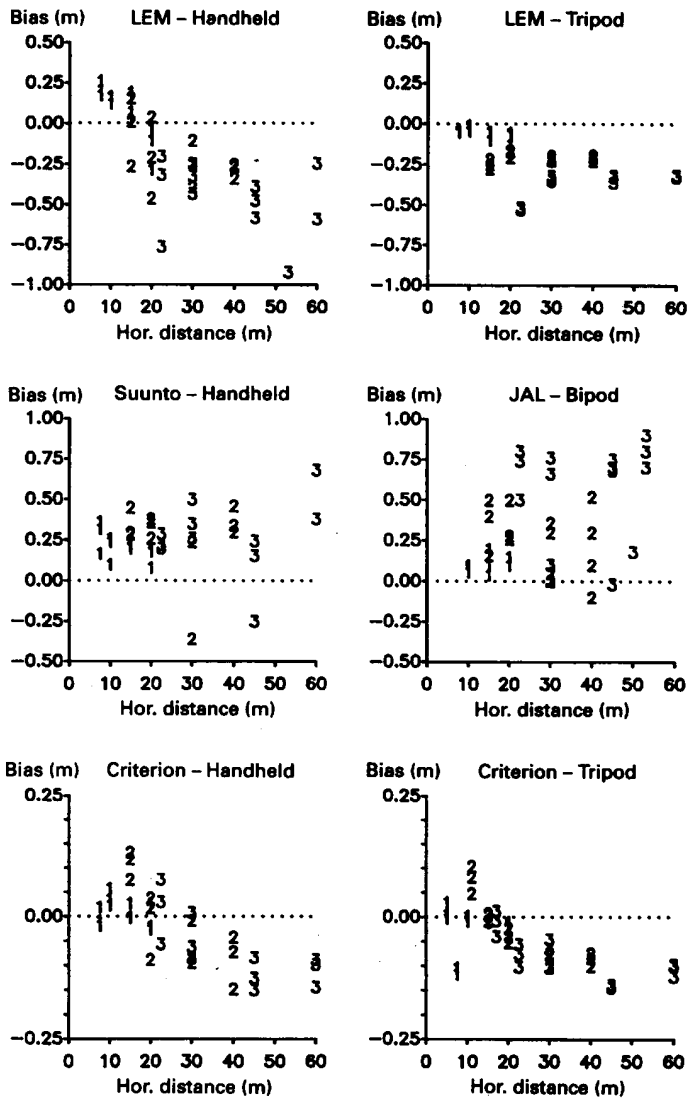

Figure 1. Bias in height estimates in controlled test. Symbols indicate height levels (1 = 10 m, 2 = 20 m, 3 = 30 m), and show means of five observations by an individual. Bias is *e = y – y^, so* negative values are overestimates. Scaling differs with instrument. (Note: Symbols may coincide. In some cases horizontal distance deviates from planned design. No observations for JAL at 7.5 m distance.)

The Criterion seems to perform better than the other three instruments, but it too shows a bias unless used at a distance of *15* m from the target (Figure 1). The pattern for the tripod-mounted Criterion seems to reflect the parallax implicit in the rifle design, and suggests that the instrument was adjusted so that the line of sight from the telescope coincides with the laser beam at 15 m. All of our height estimates made with the Criterion were within the accuracy of ± *15* cm claimed for the instrument.

In all but two instances the Suunto underestimated height (in contrast to Eriksson *(1970)* who reported a tendency to overestimate with the Suunto), and this revealed a further limitation in our experimental design. Truly independent replications would require five measurements of the distance to the target. We felt that this would have been too time-consuming in the case of the Suunto, so we used the distance pre-determined for each reference mark. Successive observations were not made consecutively, but were made only after completing a round of measurements. Despite this precaution, it appears that in at least two instances, the operator remembered the prior measurement and repeated the original mistake, presumably by misreading the angle to the target. These considerations concerning the independence of replications are less critical for the laser hypsometers which take new measurements of distance and provide a digital readout. However, our decision to take five successive laser measurements without moving the tripod (to save time, with both the LEM and the Criterion) means that we have pseudo-replications which may not reflect the true precision of the instrument under field conditions.

Table 2: Bias in height estimates (m)

Instrument	Controlled test *(n = 36)*		Field test* (hand-held)
	Hand-held	Tripod	*(n = 15)*
LEM	-0.19	-0.22	+0.19
Suunto	+0.28		+0.15
JAL		+0.36	-0.23 †
Criterion	-0.02 NS	-0.04	+0.03 NS

* test for bias in field trial is only approximate as true heights are not known; † JAL is used on a bipod in both controlled and field tests; NS not significant (P>0.05); all other values significant (P <0.05).

Table 2 summarizes the average bias detected in the instruments. The actual bias experienced in practice will depend on the particular situation (e.g. note patterns evident in Figure 1). However, since tests were standardized for all instruments, Table 2 should provide a reasonable summary for comparing performance. All results reported in this paper are statistically significant (P <0.05) unless otherwise indicated.

Figure 1 illustrates variation between operators, but it does not reveal within-operator variability, since each symbol is the mean of five observations by an operator. This provides an optimistic view of the precision of hypsometers. It is important to gain an insight into the variability within, as well as between, operators, to gauge the precision of the instruments. Figure 2 is an analogue of Figure 1, but shows the range of the individual readings rather than the bias. Here, each symbol represents the range of 15-20 observations by three to four operators. Height estimates obtained with the hand-held LEM are surprisingly erratic, but a great improvement can be attained by using a tripod (this applies to both dendrometers).

In Figures 1 and 2, the distance (m) between the target and the instrument generally seemed to be the most informative way to illustrate the systematic patterns detected. However, for the Suunto, it is informative to plot bias (and range) against the relative distance (expressed as a percentage of height; Figure 3). Unfortunately, it is not clear if Figure 3 reveals maxima, or if it reflects a step at a viewing angle of 35° (70 per cent), where the scale on the Suunto changes from ticks every 1 per cent to every 2 per cent.

Height measurement under field conditions

The controlled environment at the University provided an important test for bias, but could not provide a realistic evaluation of instrument performance under field conditions, so we also compared the instruments in a Norway spruce plantation (a dense 56-year-old stand on a level site, stocking *650* stems ha^{-1}). We measured 15 trees with each of the four instruments (none of the trees were leaning, ground level was not marked). We used the laser dendrometers both with and without a tripod, taking five replications. To maintain independence between observations, participants worked systematically through all 15 trees before returning for a replication. Much of the time required to measure tree height may be taken up in finding a suitable vantage point (generally affording a viewing angle of about 45°), so to speed the conduct of the trial, we marked a standard sighting point for each of the 15 trees. In the case of the Suunto, the distance from this point to the tree was measured only once, and that standard distance was used for all measurements. With the other instruments, operators varied the sighting position to suit personal preferences and characteristics.

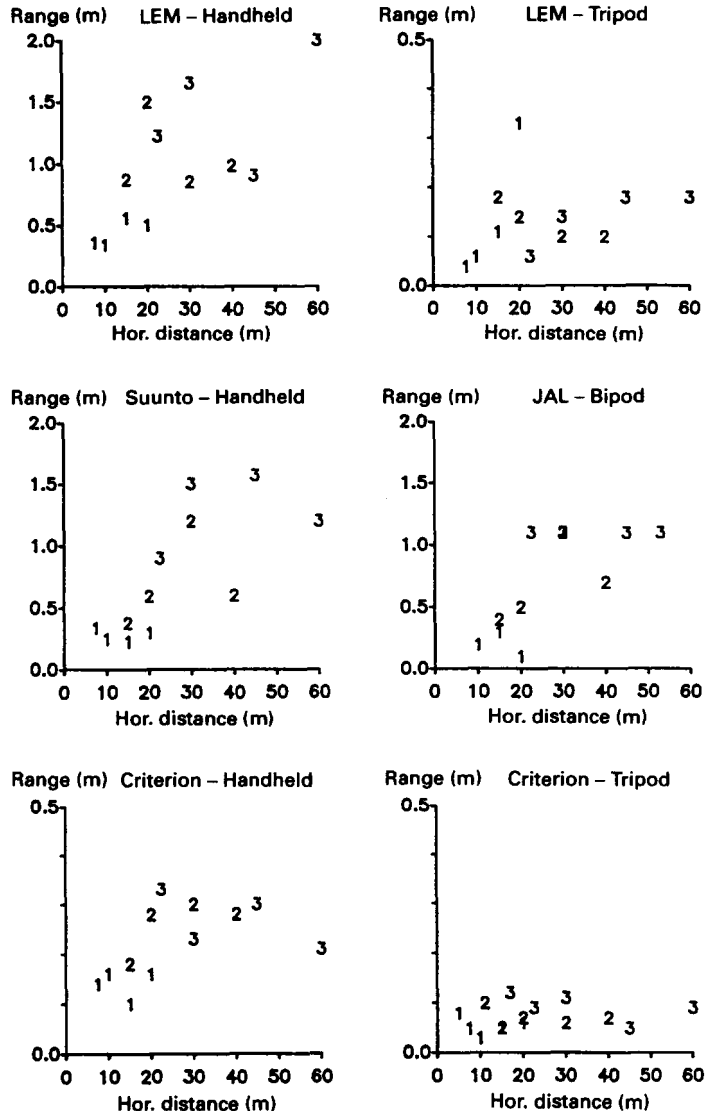

Figure 2. Variability in height estimates in controlled test. Symbols indicate height levels (1 = 10 m, 2 = 20 m, 3 = 30 m). Each point represents the range among 15-20 observations by three to four observers. Scaling differs.

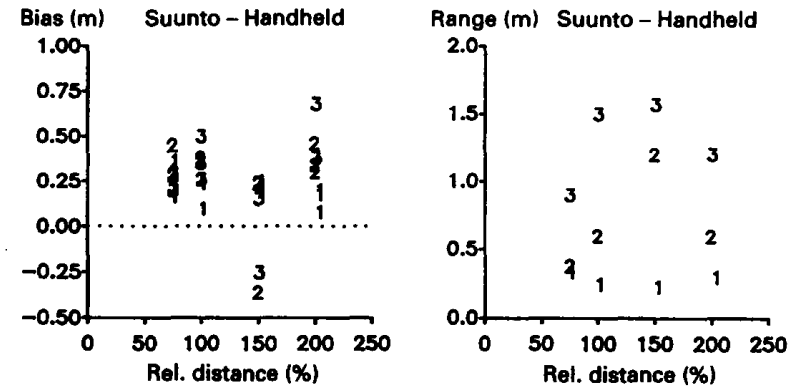

Figure 3. Bias and variability in Suunto estimates plotted against relative height (i.e. distance expressed as a percentage of height).

The true height of these trees remains unknown, so the mean of ten measurements (five observations by each of two operators) made with the tripod-mounted Criterion was assumed to be the `true' value for comparing instruments (other than the LEM). Figures 1 and 2 confirm that this should provide a reasonable basis for comparison. Because a full growth season elapsed between the field tests of the LEM and the test of the other instruments, we cannot compare the accuracy of the Criterion and the LEM directly, and use the mean of ten measurements made with the tripod-mounted LEM as the `true' value to appraise the hand-held performance of the LEM in Figure 4. We were unable to fell or climb these trees, and since the true heights remain unknown, this part of the evaluation cannot indicate bias, but merely illustrates differences between instruments. However, this test provides a good indication of the precision that may be expected under field conditions.

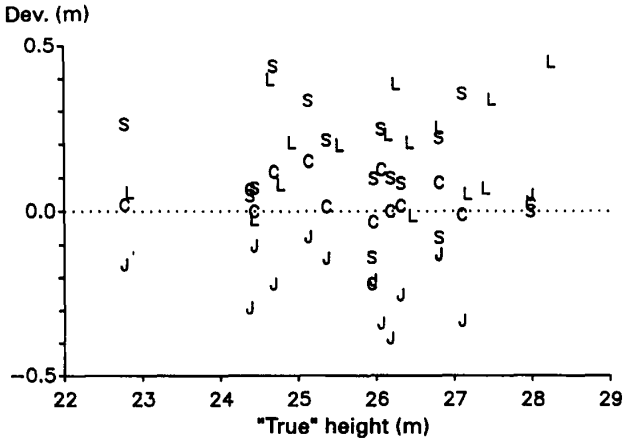

Figure 4. Deviations (Dev.) between dendrometer-tripod and other estimates of tree height. Points are means of 3-20 observations by two to four operators. One JAL point (26, -0.8) omitted. Symbols: L = LEM (hand-held), J = JAL, S = Suunto, C = Criterion (hand-held).

Figure 4 illustrates that the Suunto may underestimate relative to the Criterion, consistent with findings from our controlled test. Discrepancies in Figure 4 are smaller than those in Figure 1, despite the inclusion of data from four operators. However, these data represent the means of nine observations, compared with the means of five observations for each operator in Figure 1. The JAL underestimated consistently in the controlled test (Figure 1; each point is the mean of four or five observations by each of four operators), but appears to overestimate in the field trial (Figure 4; mean of single observations by each of three operators). Unfortunately, the cause of this discrepancy is not evident, as the two parts of the test were conducted by different individuals at different times. It is not certain if the same instrument was used in both parts of the test (due to a clerical error it is unclear if the serial number was 236 or 238, and both these instruments are in service). It is possible that we used the same instrument, and that it suffered a blow or other accidental mishandling while in storage or

transit. It is also possible that we used different instruments, and that both of these had not been calibrated recently. Either case serves to emphasize the importance of calibrating all instruments to a reliable standard at acquisition, at the start of each measurement season, and after suffering any mishandling.

The number of observers and replications in the field trial varied greatly (two to four observers and one to five replications), so it is difficult to provide an objective analysis of precision under field conditions. Therefore we use the range as an estimate of variability. Taking the mean of the range of height estimates observed for each of the 15 trees reduces the effect of any extreme values. Table 3 shows the mean range of values recorded for each instrument, in both the field and the controlled test (cf. Figure 2). Care is required in interpretation, because of the different sample sizes. The Criterion shows the expected trend: smaller ranges when tripod-mounted and under controlled conditions (two- to threefold improvement in each case). The result for the hand-held LEM in the controlled test seems abnormally high, and it seems that generally, the range of estimates obtained with the Criterion may be a little over half of those obtained with the LEM. The apparently good performance of the JAL and the Suunto in the field (relative to the controlled test) may be due to the small sample size. The benefit of using a tripod with both laser dendrometers is evident. It is not clear why the LEM performed so poorly, but we attribute it in part to operator fatigue.

The field trial provided an important test of user acceptance, even if this could only be appraised in a subjective way. When tripod-mounted, both dendrometers were slow to use and heavy to carry. Both instruments were tiring to use by hand for a prolonged period. Participants found the Criterion's gunstock-support more comfortable to use, but preferred to carry the binocular-style LEM. Both laser dendrometers offer the potential to speed up height measurement, to reduce field measurement crews, and to download height measurements directly to electronic field data recording systems (reducing risks of transcription errors, etc.). Unfortunately, they are both heavier, bulkier and more expensive than traditional hypsometers. There is clearly room for improvement in both these instruments, but either one could usefully improve the efficiency of field measurement.

Table 3: Average range of height estimates, indicating the precision attained

Instrument	Expected range (m)					
	Controlled test (*2* heights* × 4 distances)			Field test (15 sample trees)		
	Obs/ops†	Hand-held	Tripod-mounted	Obs/ops†	Hand held	Tripod-mounted
LEM	15/3	1.26	0.14	11/3	1.04	0.45
Suunto	15/3	0.99		9/4	0.88	
JAL	14/4		0.89	3/3		0.40
Criterion	15/3	0.26	0.07	10/2	0.59$	0.31

* Only the 20 and 30 m levels were used, as the range of values recorded for the 10 m level was markedly less (Figure 2); † the total number of observations used, and the number of operators involved, in the computation of each range; $ in the field test with the hand-held Criterion, 15 observations from 3 operators were used (i.e. 15/3, not 10/2).

Table 4: Bias in distance estimates (m) to various targets

Instrument	n	Without Al foil	With Al foil
LEM (on concrete)	10	+0.04	
Criterion			
concrete	10	+0.02	+0.07
dry beech	6	+0.04	+0.06
dry spruce	6	+0.02	+0.03
wet spruce	*5*	-0.03	*+0.05*

Nine replications were taken from n distances with the Criterion. Only 4 replications were taken with the LEM, only 4 distances were used for the Criterion-Al foil-concrete.

Distance measurement

Laser dendrometers rely on measurements of distance and angles to compute height, so we tested their distance-measuring capability in our attempt to find the source of the biased height estimates. We were very conscious that we were testing a sophisticated instrument with submillimetre resolution against a tape measure marked in centimetres, so we took great care to tension the tape correctly and to take two independent measurements.

Preliminary tests at the University suggested that both laser dendrometers tended to underestimate distances (to concrete walls) by about 5 cm (Figure 5, Table 4). We observed that estimated distances appeared to depend on the substance of the target, and we began to use aluminium foil as a potential standard. A single film of aluminium foil smoothed onto a target seems to reduce the estimated distance by up to 5 cm, but may be partially transparent to the laser beam, as the precision of estimates was poor and accuracy seemed to depend on the nature of the material behind the foil. We experimented with some other targets (including reflector, steel, etc.) under field conditions, but did not find a suitable standard. Most of our measurements were within the ± 10 cm accuracy claimed by the manufacturer (Figure 5), but users should be aware that estimated distances may depend on bark characteristics (e.g. species, age, dry/wet bark, etc.) and should not be led into complacency by the sub-millimetre readout available with the dendrometer.

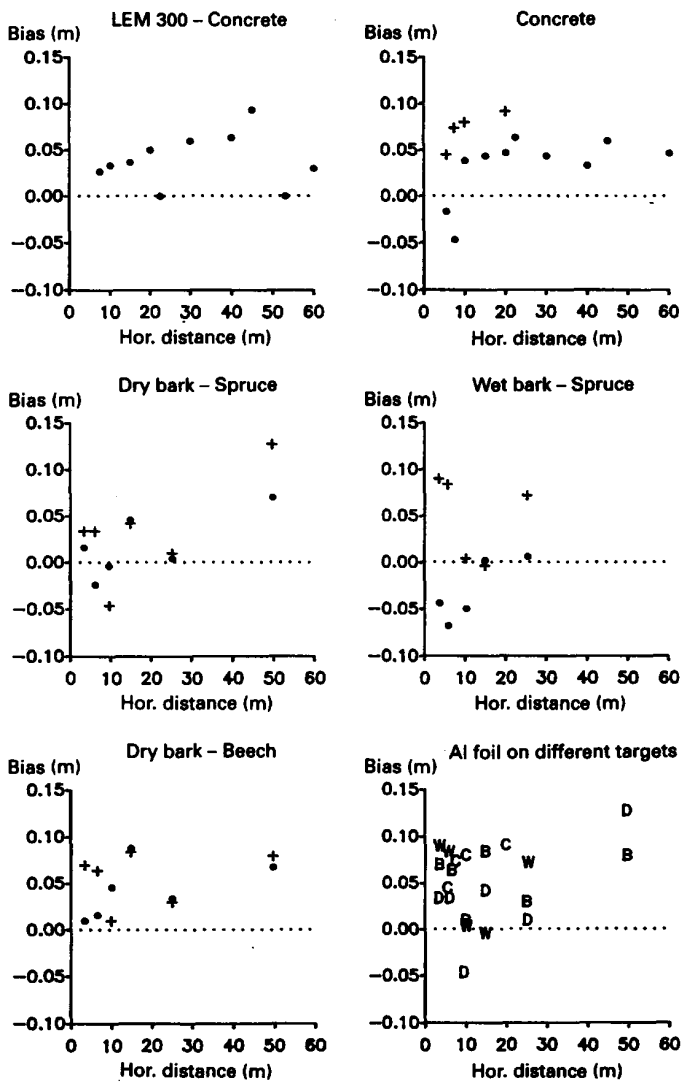

Figure 5. Bias in distance estimates from laser dendrometers. All data refer to Criterion except where otherwise indicated in first graph. Symbols: +, using aluminium foil; B, dry beech; D, dry spruce; W, wet spruce; C, concrete.

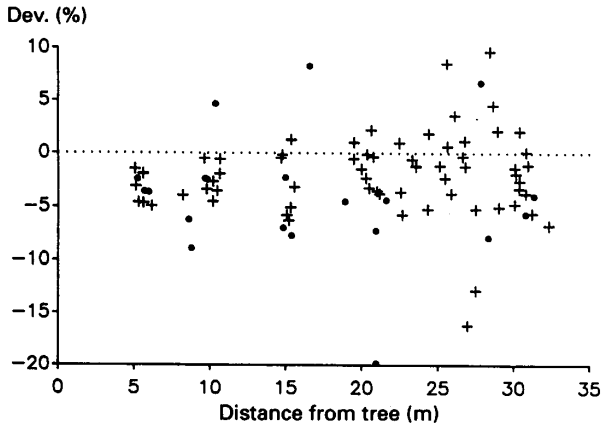

Figure 6. Deviations between remote (Criterion, +_ tripod, •= hand-held) and direct (calliper) measurements of tree diameter. Beech and spruce trees ranged from 22 to 75 cm d.b.h.

Diameter measurement

Both laser dendrometers have graticules in their viewfinders and this allows diameters to be estimated remotely. We tried the Criterion on spruce and beech trees (in an adjacent 120-year-old pure beech stand) of several sizes, from a range of distances, and found that we tended to overestimate diameters by 5 per cent (most observations within ± 10 per cent) with a hand-held Criterion, and by 2 per cent (most observations within ± 7 per cent) with a tripod-mounted Criterion (Figure 6), compared with calliper measurements made on the same axis. This is consistent with the manufacturer's claimed accuracy of ± 5 cm d.b.h. More accurate diameter estimates could be obtained by coupling an electronic theodolite or a rotating split image prism with the dendrometer (Carr, 1993).

Conclusion

Readers should make their own evaluation of their requirements and of instrument performance and cost. Each instrument purchased should be tested to a suitable standard, and this testing should be repeated regularly, after any mishandling or prolonged storage. Do not be deluded by the sub-millimetre resolution of an instrument, but check for yourself if it meets your accuracy requirements.

In modifying our procedures during this evaluation, we consciously compromised our experiment design, but saw no efficient alternative. Ideally, we should have tested both instruments at the same time, with the same operators, and benchmarked against a more reliable standard (e.g. a land surveyor's instrument rather than a tape measure). Independent tests of distance and inclination measuring ability would have provided a better understanding of the bias evident in our height estimates. If we had plotted graphs of our data immediately in the field, we probably would have decided to collect more data (especially e.g. on the measured and estimated distances to various targets) and would have been better placed to draw conclusions. And if we were to begin our trial anew, with the knowledge and experience we now have, we would do it rather differently, actively looking for possible sources of bias, and especially for the implications of different targets (e.g. the nature of the bark; smooth/rough/wet/etc.). Perhaps the greatest limitation in our design was our implicit assumption that the instruments were satisfactory, and that our trial was a formality.

Both laser dendrometers exhibited a small but significant bias. This bias was statistically significant only because of the precision of the instruments; a similar bias in traditional hypsometers might not be significant in a statistical sense (because of lower precision) and would probably remain undetected. However, the bias detected in the laser dendrometers is

also significant in a logical sense, because of their precision and their ability to provide sub-millimetre readouts which may foster complacency among users. Both instruments represent a considerable advance on previous technology, but there remains room for further improvement. We leave readers with a provocative question: is it better to compromise precision to eliminate bias, or to tolerate bias to achieve higher precision? Is the answer the same for temporary resource surveys as for permanent sample plots?

Acknowledgements
We thank our colleagues Christian Pilegaard Hansen, Bo Holm Kristensen, Thomas Stuhlmann Retsloff, the late Jerzy Wedrowski (Danish National Forest and Nature Agency) and Bruno Bilde Jorgensen (Danish Forest and Landscape Research Institute) for participating in this time-consuming, repetitive trial. Christian Pilegaard Hansen (Danish National Forest and Nature Agency) and Martin Lund Olesen (Royal Veterinary and Agricultural University, Copenhagen) kindly commented on the manuscript. Our trials were conducted with laser dendrometers kindly loaned to us by distributors for the manufacturers. Use of trade names does not imply an endorsement by the authors or their employers.

References
Anonymous 1954 JAL hypsometer. *FAO Equipment Note* A.2.54, 2pp.
Carr, B. 1993 Use of laser instruments for tree measurement: present use and future development. In *Modern Methods of Estimating Tree and Log Volume.* IUFRO Conference 14-16 June 1993, Morgantown WV, USA. G.B. Wood and H.V. Wiant (eds). West Virginia University Publication Services, pp. 10-17.
Duran, F. 1994 Tree measurement and survey laser. *John Bell & Assoc. Inc., Inventory and Cruising Newsletter 25,* 1-2.
Eriksson, H. 1970. Om matningsfel vid hojdmatning av staende trad med olika instrument. (On measuring errors in tree height determination with different altimeters.) *Institutionen for Skogsproduktion, Skogshogskolan, Rapporter och Uppsatser* Nr 19, 42pp.
Fairweather, S.E. 1994 Field tests of the Criterion 400 for hardwood tree diameter measurements. *North. J. Appl. For.* 11, 29-31.
Jasumback, T. and Carr, B. 1991 Laser tree measurement. *USDA Forest Service Technology Development Program, Timber Tech Tips,* September 1991, 5pp.
Jonsson, B., Holm, S. and Kallur, H. 1992 A forest inventory method based on density-adapted circular plot size. *Scand. J. For. Res.* 7, 405-421.
Liu, C.J. 1995 Using portable laser EDM for forest traverse surveys. *Can. J. For. Res.* 25, 753-766.
Liu, C.J., Huang, X. and Eichenberger, J.K. 1993 Using laser technology for measuring trees. In *Modern Methods of Estimating Tree and Log Volume.* IUFRO Conference 14-16 June 1994, Morgantown WV, USA. G.B. Wood and H.V. Wiant (eds). West Virginia University Publication Services, pp. 18-29.
Loetsch, F., Zohrer, F. and Haller, K.E. 1973 *Forest Inventory, Vol. II.* BLV, Munchen, 469pp.
Lovengreen, J.A. 1952 Hojdemaalere (Hypsometers). *Dan. Skovforen. Tidsskr.* 37, 590-601.
Olsen, H.C. 1968 Latent fejl pa en JAL hojdemaler (Latent defect in a JAL hypsometer). *Dan. Skovforen. Tidsskr.* 53, 289-293.
Schmid, P., Roiko-Jokela, P., Mingard, P. and Zobeiry, M. 1971 The optimal determination of the volume of standing trees. *Mitt. Forstl. BundesVersuchsanst. Wien 91,* 33-48.
Schreuder, H.T., Gregoire, T.G. and Wood, G.B. 1993 *Sampling Methods for Multiresource Forest Inventory.* Wiley, New York, 446pp.
Williams, M.S., Bechtold, W.A. and LaBau, V.J. 1994 Five instruments for measuring tree height: An evaluation. *South. J. Appl. For.* 18, 76-82.