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Estimating Timber Volume of Forest Stands Using Airborne Laser Scanner Data

*Erik Næsset**

*The stand volumes of 36 Norway spruce (*Picea abies *Karst.) and Scots pine (*Pinus sylvestris *L.) stands were derived from various tree canopy height metrics and canopy cover density measured by means of an airborne laser scanner. On average, the laser transmitted 1350–1910 pulses per stand and recorded 505–1070 canopy hits with corresponding estimates of canopy height. Ground truth stand volume was regressed against mean stand height, the mean height of all laser pulses within a stand, and canopy cover density as determined from the laser data. The coefficients of determination were in the range between 0.456 and 0.887. The coefficients of variation ranged from 17.2% to 43.3%. ©Elsevier Science Inc., 1997*

INTRODUCTION

In order to reduce the expenses of forest management planning in Norway, remote sensing techniques have become an integral part of the forest surveys. For about 50% of the area surveyed annually, the forest and tree characteristics required in the planning process are derived by aerial photointerpretation (Næsset et al., 1992). In Norway, forest management planning of individual forest holdings is usually carried out according to an area-based approach (Anon., 1995), which implies that the individual forest stands are the basic units of the surveys and the plans.

The tree volume of a stand is one of the most important stand characteristics in forest planning. Currently, stand volume is derived from field measurements of stand mean height and basal area or from photogrammetric tree height measurements and photointerpretation of crown closure. During the last 10–15 years, several experiments have been carried out in order to determine tree volume by various airborne laser profiling and lidar systems (e.g., Maclean and Krabill, 1986; Nelson et al., 1988; Nilsson, 1994). The lasers are pulsed systems that transmit a laser pulse and determine the distance to the surface (the tree canopy or the ground) according to the time taken for the pulse to travel back to the sensor. A pulse may pass vertically through a forest canopy, and there may be several secondary returns as the light from a single pulse is reflected from within canopy layers of vegetation. A sensor may record either the first or the last return, or store the whole reflected sequence. In the first case, the tree height may be calculated for the pulses not hitting the ground as the difference between the recorded return (the tree canopy) and a ground level determined from the pulses hitting the ground. In the latter case, the tree height may be calculated as the difference between the first and the last significant returns.

Several variables derived from laser profiling data may be used in the estimation of stand volume. The most important one seems to be tree height, or the mean value of the individual tree heights (e.g., Nelson et al., 1988). Measures of canopy cover density have also been computed from laser data, although the correlation between the density measures and stand volume has sometimes been low (Nilsson, 1994). The canopy cover density may be calculated as the rate of canopy hits, that is, the number of canopy hits divided by the total number of transmitted pulses.

In laser profiling a canopy profile may be derived by merging the series of tree height measurements. Hugershoff (1939) and later Maclean and Martin (1984) showed that timber volume is related to the canopy profile cross-sectional area generated by means of aerial photographs. Maclean and Krabill (1986) and Nelson et al. (1988) used canopy profile cross-sectional area generated by la-

* Department of Forest Sciences, Agricultural University of Norway, Ås, Norway

Address correspondence to Erik Næsset, Dept. of Forest Sciences, Agricultural Univ. of Norway, P.O. Box 5044, N-1432 Ås, Norway.

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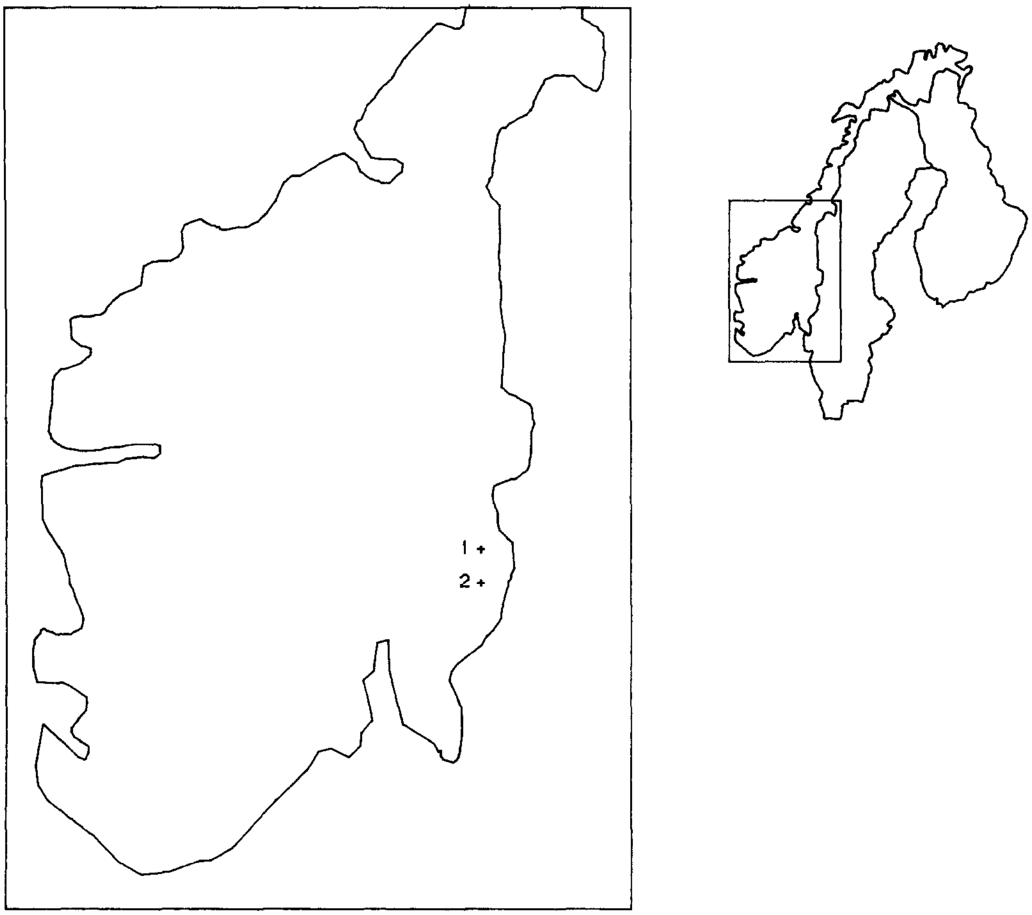

Figure 1. Map of Scandinavia indicating the location of test sites 1 and 2.

ser profiling to estimate timber volume. Thus, the cross-sectional area has been regarded as an important variable in tree volume estimation.

In the forestry experiments accomplished so far, the lasers have usually been operated in a profiling mode; that is, only a single line of data directly beneath the aircraft (at nadir) is recorded. For large-scale practical applications of laser data the profiling technique would provide a rather limited sample. Scanning laser systems would provide greater distributions of samples, although the consequences of looking through the forest canopy at an angle need to be better investigated (Leckie, 1990; Næsset, 1997). Previous experiments have also suffered from some deficiencies regarding the positioning of the laser data (e.g., Nilsson, 1994).

The Optech ALTM 1020 laser scanning system and associated TopScan software are now operated on a large-scale commercial basis (Wagner, 1995), which implies that the clients may purchase scanned postprocessed data of, for example, tree canopy height with high positional accuracy. The objective of the current study was to assess the accuracy of the estimation of volume of forest stands using such postprocessed airborne laser scanner data. Effects of forest stand conditions and the laser scan angle on errors in the estimated volume are also examined.

MATERIAL AND METHODS

Ground Truth Data (Field Inventory)

Two forest areas in the Elverum (N 60°46′ E 11°45′, 170–200 m a.s.l.) and the Grue (N 60°24′ E 11°58′, 200–

Table 1. Summary of Ground Truth Data[a]

Test Site	No. of Stands	Stand Area (ha)		Tree Species Distribution (%)			V_f (m^3/ha)		G (m^2/ha)		h_L (m)	
		Range	Mean	Spruce	Pine	Birch	Range	Mean	Range	Mean	Range	Mean
1	18	0.7–4.6	1.5	3	97	0	49–472	191	12.6–53.8	25.1	8.1–24.3	17.5
2	18	0.5–3.4	1.5	69	28	3	53–283	149	12.6–35.3	22.5	8.2–20.1	14.9

[a] V_f=stand volume, G=basal area, h_L=Lorey's mean height.

360 m a.s.l.) municipalities, Southeast Norway, were selected for the trial. The areas in Elverum and Grue are denoted as test site 1 and test site 2, respectively (Fig. 1). The stand boundaries of all the forest stands within the test sites were identified and delineated by stereoscopic photointerpretation using a second order stereoplotter and color infrared aerial photographs. The scale was approximately 1:15,000.

A total of 36 stands were selected for the study. The delineated boundaries of these stands were digitized. All the stands were covered by either Norway spruce (*Picea abies* Karst.), Scots pine (*Pinus sylvestris* L.), or a mixture of the two species. However, test site 1 was covered mainly by Scots pine (97%, Table 1), whereas test site 2 was dominated by Norway spruce (69%). The ground truth stand volume (V_f), stand density as expressed by the basal area (G), and stand mean height as expressed by the so-called Lorey's mean height (h_L), that is, mean height weighted by basal area, varied significantly between the stands (Table 1). The age of the stands ranged from 31 years to 145 years.

The ground truth data were collected by Eid (1996). Several sample plots were distributed systematically within each stand. The average number of plots per stand was 14 and 15 for test sites 1 and 2, respectively. The plot area was 100 m^2 in young stands and 200 m^2 in mature stands. On each plot, the heights of sample trees selected by horizontal point sampling were measured by a Vertex hypsometer. At least one sample tree was selected on each plot, and the average numbers of sample trees per stand were 18 and 26 for test sites 1 and 2, respectively. All trees with diameter at breast height >4 cm and >10 cm were callipered in young and mature stands, respectively. The volume of each tree was computed by means of volume equations for individual trees, and stand volume was computed as the average of the individual sample plot volumes within each stand. A summary of the ground truth data is displayed in Table 1.

Laser Scanner Data

A Piper PA31-310 aircraft carried the Optech ALTM 1020 laser scanning system. The laser transmits at 1047 nm (near-infrared). The major components of the ALTM 1020 are the infrared laser, the scanner transmitting the laser pulse and receiving its reflected echo, the time interval meter measuring the elapsed time between transmittance and receipt, the global positioning system airborne and ground receivers, and the inertial reference system reporting the aircrafts's roll, pitch, and heading.

The laser scanner data were acquired 20 October 1995. The plane was flown 640–825 m above the ground (Table 2) at a speed of approximately 80 m/s. Several parallel flightlines were flown. The pulse repetition frequency was 2 kHz and the scan frequency was 7 Hz. Maximum scan angle (off nadir) was 20°, which according to the flying height corresponded to an average swath width of about 460–600 m. However, the maximum scan angle for the selected test stands was 19.2° (Table 2). The overlap between adjacent flightlines was about 70–425 m. The beam divergence of 0.25 mrad produced a roughly circular spot size on the ground ("footprint") with a diameter of about 13–16 cm. The average distance between footprints in the test stands was 2.8–3.3 m.

The main purpose of the current laser data acquisition was to generate a digital elevation model (DEM). The laser scanning system was therefore operated such that only the last returns of the laser pulses were recorded. It should be noted that all distances measured by the laser at an off nadir angle, that is, distances to the ground as well as to the tree canopy, were automatically converted to vertical distances. A complete postprocessing was undertaken by TopScan GmbH, Germany. In the postprocessing, the pulses that hit the ground were selected. A DEM was generated from these pulses. The ellipsoidic height accuracy of differentially corrected, and processed ALTM 1020 data was about 25–30 cm (Opseth, 1996). The remaining pulses were considered to represent tree canopy hits. The tree canopy height was computed as the difference between the latter pulses and the corresponding DEM values. Observations with a height value less than 2 m were excluded from the dataset in order to eliminate the effect of stones, shrubs, etc. The data were referenced to the local coordinate system used for the digitized stand boundaries. For each test site, two laser datasets were developed: 1) position-corrected data on tree canopy heights and 2) position-corrected coordinates for all transmitted laser pulses. Differentially corrected coordinates for the flightlines were generated also.

Computations

The stand boundary map layer was spatially registered to the laser data by means of a geographical information system. Laser-based estimates of canopy heights, the number of canopy hits, and the number of transmitted pulses were calculated for each of the stands. The number of transmitted pulses and canopy hits varied significantly between the stands (Table 2).

The aircraft flightlines were also registered to the stand map. The distance between the centroid of each stand (polygon) and the adjacent flightline was measured perpendicular to the flightline and the off nadir angle was computed (Table 2).

Multiple regression analysis was used to develop models for stand volume related to predictor variables derived from the laser data. Three predictor variables were tested: 1) mean stand height, 2) mean height of all laser pulses within a stand, and 3) mean canopy cover density.

The computation of *mean stand height* from the la-

Table 2. Summary of the Laser Scanner and Flight Data

Test Site	Mean Flying Height (m)	Mean Footprint Diameter (cm)	No. of Transmitted Pulses per Stand		No. of Canopy Hits per Stand		Scan Angle for the Selected Stands (deg)	
			Range	Mean	Range	Mean	Range	Mean
1	825	16.5	625–2925	1350	174–894	505	0.8–19.2	6.7
2	640	12.8	440–6457	1910	133–3820	1070	0.9–14.3	8.1

ser data followed the approach proposed by Næsset (1997). For each stand, a regular grid was laid atop the laser data comprising the canopy heights. The size of the individual grid cells was 15 m×15 m. All laser values except the largest one within each grid cell were discarded. The average laser height of a stand was computed as the mean value of the selected laser observations within the individual cells. The number of laser measurements within each cell was used as weights, such that the significance of each of the selected laser heights was proportional to the number of observations they represented. This laser mean height was denoted as h_{15}.

In the current material, Næsset (1997) showed that h_{15} estimated h_L quite well. Mean differences between h_{15} and h_L in the range between -0.4 m and 0.1 m and standard deviations for the differences of 1.2–1.3 m were reported. The applied method for determination of h_{15} seemed to work well for tree species with relatively broad crowns (Scots pine) as well as for species with more conical crown forms (Norway spruce).

Mean height of all laser pulses within a stand (h_a) was computed for each stand as the sum of the height values of the laser pulses classified as canopy hits divided by the total number of transmitted pulses. Since scanner data is distributed in two spatial dimensions and not along a single transect (one dimension) as is the case in laser profiling, one might compute the volume below the canopy surface as a metric corresponding to the canopy profile cross-sectional area derived from profiling data. Thus, h_a may be regarded as a per areal unit normalized volume below the canopy surface. h_a is directly related to the volume below the canopy surface [volume below the canopy surface=(stand area)$\times h_a$].

Mean canopy cover density (D) was calculated according to an approach corresponding to the mean stand height computation outlined above. For each stand, the regular grid with 15 m×15 m grid cells used for the mean height computation was laid atop the laser data comprising the canopy heights and the laser data comprising all transmitted pulses. For each grid cell, the density was computed as the number of canopy hits divided by the number of transmitted pulses. For grid cells in which no canopy hits were recorded, the density was set to 0. The average canopy cover density of a stand was computed as the mean value of the individual cell densities. The area of each cell was used as weights in order to reduce the influence of "sliver cells" with size less than 15 m×15 m occurring along the stand boundaries.

In the multiple regression analysis, multiplicative models were estimated as linear regressions in the logarithmic variables, and then converted back to original scale by adding half of the variance to the intercept before conversion (Goldberger, 1968). Each test site was treated separately, and two models were developed for each site. Since the current material comprised 36 observations only, all observations were reserved for the regression analysis. Thus, no observations were available for testing (verification) of the regressions.

Finally, simple correlation analysis was considered in order to examine effects of stand conditions and the laser scan angle on the residuals in stand volume determined from the laser data.

RESULTS

First, stand volume was regressed against laser mean stand height and mean canopy cover density using a multiplicative model, that is,

$$V_f=\beta_0 h_{15}^{\beta_1} D^{\beta_2} , \qquad \text{(A)}$$

where

V_f=total volume per hectare inclusive bark (m^3/ha),
h_{15}=laser stand mean height (m),
D=mean laser canopy cover density (%).

The estimated models for test sites 1 and 2 were denoted model 1A and model 2A, respectively. The coefficient of determination (R^2) was 0.472 for test site 1 and 0.838 for test site 2 (Table 3). The correlation in model 2A was significantly higher than in model 1A at the 5% level. The coefficient of variation (CV) was 42.7% and 20.9% after conversion of the regressions to original scale. For both test sites, the statistical significance of the regression coefficients indicated that models represented by Eq. (A) were more appropriate than models with h_{15} as the only independent variable.

Principal component analysis based on the correlation matrix was used to assess the presence of collinearity. The square root of the largest eigenvalue divided by the smallest eigenvalue (condition number) was used as a means for suggesting collinearity. The condition numbers (κ) for models 1A and 2A were 1.1 and 1.4, respectively.

Table 3. Regression Coefficients, Coefficient of Determination (R^2), Square Root of Mean Square Error (RMSE), Coefficient of Variation (CV), and Condition Number (κ) for Stand Volume Regressions[a]

Variable	*Model 1A*	*Model 2A*	*Model 1B*	*Model 2B*
Intercept (corr.)	2.595 NS	2.150 NS	4.220 NS	4.211 NS
h_{15}	1.771°°°	1.706°°°	0.886 NS	0.816 NS
D	0.809°	0.667°		
h_a			0.787 NS	0.823°°
Logarithmic scale				
R^2	0.744	0.796	0.726	0.836
RMSE	0.306	0.243	0.317	0.218
CV	6.0	5.0	6.2	4.5
κ	1.1	1.4	3.4	3.1
Original scale				
R^2	0.472	0.838	0.456	0.887
RMSE (m^3/ha)	81.8	31.3	82.8	26.1
CV (%)	42.7	20.9	43.3	17.2

[a]Level of significance: NS=not significant (>0.05); ° <0.05; °° <0.01; °°° <0.001. h_{15}=laser stand mean height (m), D=mean laser canopy cover density (%), h_a = mean height of all laser pulses within a stand (m).

Stand volume was also regressed against laser mean stand height and mean height of all laser pulses within a stand according to the following model:

$$V_f=\beta_0 h_{15}^{\beta_1} h_a^{\beta_2}, \qquad \text{(B)}$$

where

V_f=total volume per hectare inclusive bark (m^3/ha),
h_{15}=laser stand mean height (m),
h_a=mean height of all laser pulses within a stand (m).

The estimated models for test sites 1 and 2 were denoted model 1B and model 2B, respectively. The coefficient of determination was 0.456 and 0.887 for test sites 1 and 2, respectively. The corresponding CV values were 43.3% and 17.2%. The correlation in model 2B was significantly higher than in model 1B. For test site 1, the level of significance of the regression coefficients indicated that a regression based on h_{15} only was just as good as model 1B. For test site 2, model 2B was significantly better than a simple model with h_{15}. The condition number was 3.4 and 3.1 for models 2A and 2B, respectively.

Correlation analysis was used to assess effects of stand conditions and the laser scan angle on the residuals in stand volume determined from the laser data. In this analysis the residuals of models 1A (test site 1) and 2A (test site 2) were studied. The residuals were computed as the differences between predicted stand volume (V_p) and stand volume measured in the field (V_f).

First, the correlation between the residuals and the off nadir scan angle (OFFNADIR) was computed. Secondly, the correlations between the residuals and individual stand variables assumed to influence the laser measurements were computed. These stand variables were forest stand age (A) and tree species. The study of stand age was motivated by the fact that the development of tree height and tree crown width are closely related to the age of a tree. The tree species were stratified according to the volume of each species. Three categories were used, namely, 1) spruce (spruce volume >75% of total stand volume), 2) pine (pine volume >75% of total stand volume), and 3) mixed coniferous (pine volume <75% and spruce volume <75% of total stand volume). The three species categories were represented by two dummy variables (SPDUMMY1 and SPDUMMY2) in the following way:

mixed:	SPDUMMY1=0	and	SPDUMMY2=0
spruce:	SPDUMMY1=1	and	SPDUMMY2=0
pine:	SPDUMMY1=0	and	SPDUMMY2=1.

None of the computed correlation coefficients were significant in the statistical sense. A correlation for test site 2 of 0.313 was found between the residuals and stand age (Table 4). For both test sites, positive correlation was found between the residuals and the off nadir

Table 4. Correlation between Residuals in Laser Data Volume Equations (V_p-V_f) Based on Models 1A (Test Site 1) and 2A (Test Site 2), and Various Characteristics Affecting the Laser Measurements[a]

Variable	*Correlation with (V_p-V_f)* Test Site 1	Test Site 2
A	−0.116 NS	0.313 NS
OFFNADIR	0.217 NS	0.013 NS
SPDUMMY1		0.100 NS
SPDUMMY2	−0.045 NS	−0.244 NS

[a]Level of significance: NS=not significant (>0.05). V_f=total volume per hectare inclusive bark measured in the field (m^3/ha), V_p=total volume per hectare inclusive bark predicted from the laser data (m^3/ha), A=stand age (years), OFFNADIR=off nadier scan angle (deg), SPDUMMY1=dummy variable representing spruce forest, and SPDUMMY2=dummy variable representing pine forest.

scan angle, although the values were rather small (0.013 and 0.217). For SPDUMMY2 representing pine forest the computed correlation coefficients were negative. The correlation for SPDUMMY1 was not estimated for test site 1 since pure spruce stands were not represented in the material (cf. Table 1).

DISCUSSION AND CONCLUSIONS

The results of the current study, though limited in the total number of observations, indicated that large differences in the applicability of laser scanner data for timber volume estimation may occur between different forest types. Test site 1 showed a coefficient of determination of 0.456–0.472 (Table 3), which was significantly smaller than the R^2 value of 0.838–0.887 found for test site 2. Although the applicability of the laser data differed between the sites, the coefficients of determination for all the estimated regressions seem to correspond to previous findings. R^2 values in the range between 0.52 and 0.78 have been reported from the use of laser profiling data (Maclean and Krabill, 1986; Nelson et al., 1988; Nilsson, 1994). Furthermore, it is interesting to note that for test site 2 the regressions fitted the laser data even better than what is usually expected for regressions based on data from aerial photointerpretation. For volume regressions estimated from photogrammetric tree height measurements and photointerpreted crown closure of more than 800 Norway spruce and Scots pine plots using 1:15,000 to 1:20,000 aerial photographs, Tomter (1988) reported R^2 values of 0.70–0.79 and coefficients of variation in the range 23.3–29.9%. It was stated that these findings correspond to the results of several Scandinavian investigations of spruce and pine.

The current analysis also revealed that it may be necessary to calibrate individual volume equations for different tree species. The negative correlation between the residuals and the SPDUMMY2 variable representing pine forest (Table 4) indicated that a common volume equation for Norway spruce, Scots pine, and various mixtures of the two species will tend to underestimate the true volume in pure pine stands. A benefit of including species information in volume equations for pure and mixed stands of loblolly pine and oak was documented by Maclean and Krabill (1986). On the other hand, no significant effect of species information was detected in an equation based on four different pine species (Nelson et al., 1988). Further analysis should therefore be carried out in order to identify which species may be treated simultaneously.

Several factors may have caused the diverging results obtained for the two test sites. Although fitting of individual volume equations is recommended for some tree species in order to avoid calibration problems, the tree species composition of each site with a 97% pine cover of test site 1 and a 69% spruce cover of test site 2 (Table 1) can hardly explain more than a small part of the differences. Test site 1, however, covers a range of ground truth volume values twice as wide as test site 2 (Table 1). The ranges of density values (G) and tree height values (h_L) are wide also. Even though the current material is too small to be divided into more homogenous subgroups for further analysis, the results may indicate that some kind of stratification of the observations should be carried out prior to fitting of volume equations in practical surveys. According to previous experiments, it appears that careful calibration to forest types as determined by other techniques is required (Leckie, 1990).

A small footprint diameter would probably be advantageous for discriminating canopy cover densities (Nelson et al., 1984). The footprint diameter for test site 2 of 12.8 cm (Table 2) may therefore have affected the estimates of canopy cover density in a positive manner compared to the footprint diameter for test site 1 of 16.5 cm. The Optech ALTM 1020 laser scanning system is designed for a high rate of penetration through the foliage, which is advantageous for DEM generation. According to previous findings, increasing the beam divergence would probably reduce the bias of direct stand height estimates (Aldred and Bonnor, 1985). However, even for small footprint diameters, the use of the grid approach to the determination of mean tree height from laser data seems promising (Næsset, 1997). Since the appropriateness of stand volume derived from mean height and canopy cover density depends on the quality of the height and density measures, small footprint diameters may be advantageous for volume estimation.

Although canopy height usually explains much of the variation noted in ground-measured tree volume (e.g., Nelson et al., 1988), the inclusion of mean canopy cover density had a significant impact on the regressions (Table 3). So did mean height of all laser pulses within a stand (h_a) too, at least for test site 2 (model 2B). The first finding seems to be in contrast to the results reported previously. Nelson et al. (1988) stated that laser variables related to canopy density were of limited value for predicting volume, whereas Nilsson (1994) rejected regression equations with canopy density due to low correlation with true stand volume. One reason for the diverging results may be the footprint diameter. Nilsson (1994) used footprint diameters which probably were at least five times larger than those in the current experiment. As noted above, small footprint diameters would probably be advantageous for discriminating canopy cover densities.

The significant impact of h_a indicates that this laser variable might be of interest in practical volume estimation. Although h_a is related to the tree heights (h_{15}), the inclusion of h_a in models 1B and 2B did not seem to cause any serious collinearity problems. The condition number (κ) was not larger than 3.4 in any of the estimated regressions (Table 3). A condition number larger

Than 30 has been proposed as a means for suggesting collinearity (Weisberg, 1985). All three examined explanatory variables (h_{15}, h_a, D) probably could be included simultaneously in volume equations, provided that this would not cause any collinearity problems. This was not tried in the current study due to a limited number of observations.

In Norway, determination of stand volume is often carried out as part of large forest surveys, frequently covering about 100–500 km^2. Such stand-by-stand surveys based on field measurements or photointerpretation usually are followed by stratified systematic field sample plot inventories in order to calibrate the timber volume estimates of the stand surveys. By means of two-phase sampling the sample plot inventories with georeferenced sample plots might provide an efficient means for stratified calibration of stand volume regressions derived from laser measurements. Stand density (basal area or crown closure), which is highly correlated with stand volume, would be suitable for stratification. As noted above, the correlation analysis (Table 4) indicated that such stratification might be arranged according to tree species too. The stand age (A) might be a third stratification criterion, although the current material provided rather weak support for such recommendations in the statistical sense (Table 4). Provided that suitable characteristics for efficient stratification could be found, the forest stands to be surveyed by practical surveys could be divided into strata in a more homogenous way than the current material. Since the present analysis was based on a rather heterogenous sample of stands regarding tree species composition, timber volume, stand density, and tree heights (Table 1), a stratified calibration of volume equations from laser measurements might provide more precise estimates of the true stand volume than indicated here.

The correlation between the residuals and the off nadir scan angle was not statistically significant (Table 4). When tree heights are measured with a laser at an angle and the heights are converted to vertical distances, the tree heights may underestimate the true stand height (Næsset, 1997). On the other hand, the probability of hitting a tree crown by a laser pulse increases by increasing the scan angle, and hence inflates the value of canopy cover density measures. Thus, two of the most relevant explanatory variables for timber volume estimation may be affected differently by scan angle. Although the effect of moderate off-nadir scan angles on volume estimation probably is limited, increasing the flying height and/or restricting the swath width would reduce such angle problems. The exact effects of looking through the canopy at different angles should therefore be better quantified.

The laser provided a widely scattered sample of laser measurements with small footprint diameters (Table 2). The effects of area coverage on the stand volume estimation was not treated in this study. Although some research have been conducted on the effect of sampling density on tree height determination (e.g., Nilsson), such studies on volume determination seem to be lacking; neither have effects on volume estimation of footprint diameter been systematically mapped. Thus, effects of sampling density and footprint size on estimation of timber volume need to be better examined in order to optimize the laser data collection for practical purposes.

The current study may indicate that laser scanner data could be used to obtain estimates of forest stand volumes with an accuracy equal to that of present inventory methods based on aerial photointerpretation, at least if careful stratification according to forest types is provided. However, the study was based on a rather limited sample of forest stands and the laser scanning system was not operated in an optimal manner for derivation of forest tree characteristics. Thus, the analysis indicates a potential for improvements of stand volume determination by laser scanning technology. Further research on extraction of forest characteristics should therefore be carried out with laser scanners properly calibrated for forestry applications.

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