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ISPRS Journal of Photogrammetry & Remote Sensing 52 (1997) 49–56

PHOTOGRAMMETRY
& REMOTE SENSING

Determination of mean tree height of forest stands using airborne laser scanner data

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Received 3 May 1996; accepted 12 December 1996

Abstract

The mean tree height of forest stands is a crucial stand characteristic in forest planning. Currently, the mean tree height is determined by field measurements or by photogrammetric measurements utilizing aerial photographs. In this study, mean tree height of 36 test stands is derived from tree canopy heights measured by means of an airborne laser scanner. On the average the laser recorded 505–1070 canopy heights per stand. First, the laser mean height is computed as the arithmetic mean of the canopy heights within each stand. The laser mean height underestimates the ground truth mean height by 4.1–5.5 m. Second, a weighted mean of the laser canopy heights is computed. The individual height values are used as weights. The weighted mean height underestimates the true height by 2.1–3.6 m. Finally, the laser mean height is computed as the arithmetic mean of the largest laser values within square grid cells with cell sizes of 15–30 m. The bias of the laser estimates is in the range −0.4 m to 1.9 m. The standard deviation for differences between the laser mean heights and the ground truth mean height is 1.1–1.6 m.

Keywords: forest inventory; laser scanning; tree heights

1. 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 photo interpretation (Næsset et al., 1992). In Norway, forest management planning of individual forest holdings is usually carried out according to an area-based approach (Anonimous, 1995), which implies that the individual forest stands are the basic units of the surveys and the plans.

The mean tree height of a stand is one of the most important stand characteristics in forest planning. Currently, the stand mean height is determined by field measurements of objectively selected sample trees or by photogrammetric height measurements of subjectively selected trees using aerial photographs. However, determination of mean tree height by the current methods is time consuming and expensive.

During the last 10–15 years several experiments have been carried out in order to determine tree heights by various airborne laser profiling and lidar systems (e.g. Nelson et al., 1984; Aldred and Bonnor, 1985; Nilsson, 1994). The lasers are pulsed systems

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PII S0924-2716(97)00002-6

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 would be several returns of the pulse. A laser may then either record 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 returns.

In the forestry experiments accomplished so far the lasers have usually been operated in a profiling mode, i.e. 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). Previous experiments have also suffered from some deficiencies regarding the positioning of the laser data (Nilsson, 1994).

The Optech ALTM 1020 laser scanning system and the joined TopScan software are now operated at a large-scale commercial basis (Wagner, 1995), which implies that the clients may purchase scanned post-processed data of, for example, tree canopy height with high positional accuracy. The objective of the current study was to assess the accuracy of the determination of mean tree height of forest stands using such post-processed airborne laser scanner data. It has been shown that the mean height determined from laser data often underestimates the true mean height (Aldred and Bonnor, 1985; Nilsson, 1994). Thus, two new approaches to the estimation of mean height, which aim to reduce the bias, are presented. Finally, effects of forest stand conditions and the laser scan angle on the stand height determined from the laser data are examined.

2. Materials and methods

2.1. Field reference data

Two forest areas in the Elverum (60°46′N 11°45′E, 170–200 m a.s.l.) and the Grue (60°24′N 11°58′E, 200–360 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. The stand boundaries of all the forest stands within the test sites were identified and delineated by stereoscopic photo interpretation using a second-order stereoplotter and colour 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.), Scotch pine (*Pinus sylvestris* L.), or a mixture of the two species. However, test site 1 was covered mainly by Scotch pine (97%, Table 1), whilst test site 2 was dominated by Norway spruce (69%). The stand density, as expressed by the basal area (G), varied significantly between the stands (Table 1). The age of the stands ranged from 31 to 145 years.

The field reference 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,

Table 1
Summary of the stand reference data

Test site	No. of stands	Stand area (ha)		Tree species distribution (%)			G (m^2/ha)		h_L (m)	
		range	mean	spruce	pine	birch	range	mean	range	mean
1	18	0.7–4.6	1.5	3	97	0	12.6–53.8	25.1	8.1–24.3	17.5
2	18	0.5–3.4	1.5	69	28	3	12.6–35.3	22.5	8.2–20.1	14.9

G = basal area.
h_L = Lorey's mean height.

sample trees were selected with probabilities proportional to their basal area. The average numbers of sample trees per stand were 18 and 26 for test sites 1 and 2, respectively. The height was measured for all the sample trees, and for each stand the stand mean height was computed as the arithmetic mean of the individual sample trees. This mean height corresponds to the so-called Lorey's mean height (h_L), and it was used as ground truth. A summary of the stand reference data is displayed in Table 1.

2.2. Laser scanner data

A Piper PA31-310 aircraft carried the Optech ALTM 1020 laser scanning system. The laser is transmitting at 1047 nm (infrared). The major components of the ALTM 1020 is 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 aircraft's roll, pitch and heading.

The laser scanner data were acquired on 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. Thus, about 0.2% of the area was sampled.

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. A complete post-processing was undertaken by TopScan GmbH, Germany, which implies that a single dataset comprising positional corrected data on tree canopy heights was provided for the present study. In the post-processing, the pulses that hit the ground were selected. A DEM was generated from these pulses. The ellipsoid height accuracy of differentially corrected and processed ALTM 1020 data is 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. Differentially corrected coordinates for the flightlines were supplied too.

2.3. Computations

The stand boundary map layer was laid over the laser data by means of a geographical information system (GIS) such that the canopy heights of the laser dataset were assigned to the individual test stands. The number of laser observations per stand representing canopy hits varied significantly between the stands (Table 2).

The stand boundary map layer was also laid over the flightlines. The ground plane 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).

The mean value of the laser observations within

Table 2
Summary of the laser scanner and flight data

Test site	Mean flying height (m)	Mean footprint diameter (cm)	No. of canopy hits per stand		Scan angle for the selected stands (degrees)	
			range	mean	range	mean
1	825	16.5	174–894	505	0.8–19.2	6.7
2	640	12.8	133–3820	1070	0.9–14.3	8.1

the individual stands, i.e. the average canopy height, was compared to the stand mean height (h_L) determined from the field measurements. However, three different approaches to the computation of the mean value of the laser observations were considered. First, the average value for each stand was computed simply as the arithmetic mean of the individual laser observations. This mean height was denoted as h_{h1}.

In the computation of the mean height from the field measurements, the height of an individual tree was weighted according to its basal area, as is often the case in practical forest surveys. Thus, the big trees have a larger impact on the mean height than the small trees. It seems logical that such an approach could also be applied to the computation of mean height from the laser data. Since the basal area of a tree is highly correlated with its height, the value of an individual laser height may be weighted by itself, or even by the square of itself. Such computations were undertaken. The mean heights computed using the original values of the laser dataset and the square of the original values as weights were denoted as h_{h2} and h_{h3}, respectively.

Another way of increasing the importance of the largest values of the laser data, is simply to exclude the smallest values from the dataset. However, since the tree heights may vary from one part of a stand to another, the inclusion of only the largest laser values may imply exclusion of major parts of a stand. If not all regions of a stand are fairly equally represented, there may be a risk that a large number of laser heights are rejected whose values certainly would affect the stand's mean height estimate. Thus, an approach to the estimation of the average laser height of a stand ensuring representation of all regions was considered.

First, a regular grid covering all the stands was generated for each of the test sites using a GIS. The size of the individual grid cells was 15 × 15 m. For each test site, the grid layer was laid over the stand boundary layer and the laser data, such that all superfluous grid cells and laser heights could be excluded. The resulting overlay for one of the test stands is shown in Fig. 1. Only the largest laser value within each grid cell was kept. Finally, the average laser height of a stand was computed as the mean value of the selected laser observations

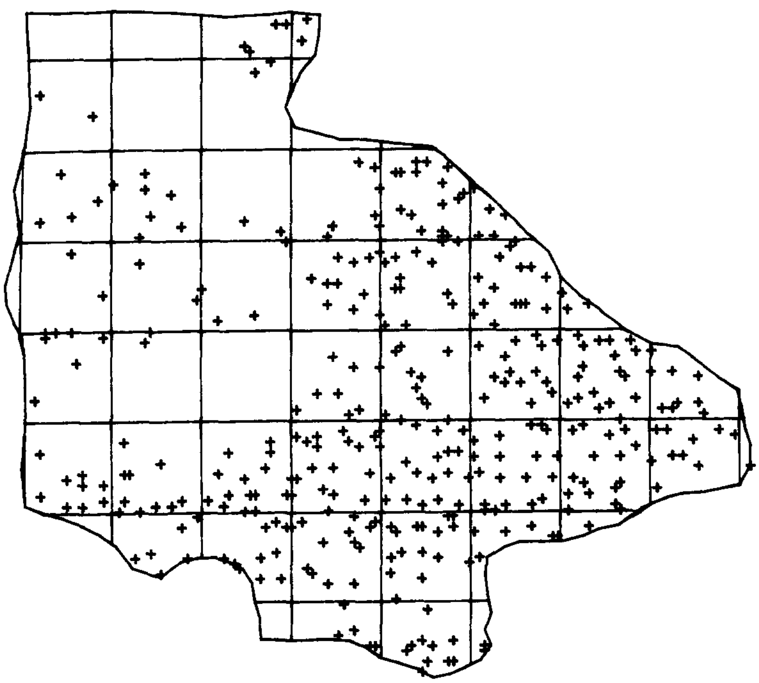

Fig. 1. Overlays of the laser dataset, a grid layer, and a polygon of the stand map layer.

within the individual cells. However, 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 $h_{15\times15}$. Computations with grid cells of 20×20 m and 30×30 m were undertaken too. The corresponding mean height estimates were denoted as $h_{20\times20}$ and $h_{30\times30}$, respectively.

The mean differences between the stand height estimated according to the laser data and the ground truth height (h_L) were evaluated. The corresponding standard deviations were also assessed. Let D_i denote the difference between the laser mean height (h_{h1}, h_{h2}, h_{h3}, $h_{15\times15}$, $h_{20\times20}$, or $h_{30\times30}$) and ground truth h_L for stand i, $i = 1, 2, \ldots, n$. The mean difference was computed with:

$$\bar{D} = \frac{1}{n}\sum_{i=1}^{n} D_i$$

The standard deviation for the differences was computed with:

$$\mathrm{SD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(D_i - \bar{D})^2}$$

The statistical significance of the mean differences, i.e., whether systematical differences were present, was assessed by means of two-tailed t-tests.

Finally, regression analysis was used to examine the effects of stand conditions and the laser scan angle on the stand height determined from the laser data.

3. Results

The arithmetic mean of the laser heights (h_{h1}) was compared to the ground truth stand mean height (h_L). The individual test sites were treated separately. The mean laser height underestimated the ground truth by 4.1–5.5 m (Table 3). The standard deviation for the differences between h_{h1} and h_L was 1.3–1.6 m. The differences between test sites regarding bias was significant at the 1% level, whilst the standard deviation did not differ significantly between the sites.

Table 3
Mean difference ($\bar{D}$) between laser stand mean height and reference stand mean height (h_L), and standard deviation (SD) for the differences

Test site	Comparison	Mean h_L (m)	$\bar{D}$ (m)	SD (m)
1	$h_{h1} - h_L$	17.5	−4.1 ***	1.6
1	$h_{h2} - h_L$	17.5	−2.9 ***	1.4
1	$h_{h3} - h_L$	17.5	−2.1 ***	1.4
1	$h_{15\times15} - h_L$	17.5	−0.4 NS	1.3
1	$h_{20\times20} - h_L$	17.5	0.3 NS	1.3
1	$h_{30\times30} - h_L$	17.5	1.1 **	1.3
2	$h_{h1} - h_L$	14.9	−5.5 ***	1.3
2	$h_{h2} - h_L$	14.9	−3.6 ***	1.1
2	$h_{h3} - h_L$	14.9	−2.3 ***	1.1
2	$h_{15\times15} - h_L$	14.9	0.1 NS	1.2
2	$h_{20\times20} - h_L$	14.9	0.9 **	1.2
2	$h_{30\times30} - h_L$	14.9	1.9 ***	1.3

Level of significance: NS = not significant (>0.05); * = <0.05; ** = <0.01; *** = <0.001.

The underestimation of the ground truth height was significantly reduced by the use of the weighted approach (h_{h2} and h_{h3}) to the computation of mean laser height. The mean differences between the weighted laser heights and the ground truth were in the range −2.1 m to −3.6 m. The standard deviations were 1.1–1.4 m.

Also the grid approach to the computation of mean height provided less biased estimates than h_{h1}. The mean differences between the mean laser heights computed by the grid approach ($h_{15\times15}$, $h_{20\times20}$, and $h_{30\times30}$) and the ground truth were between −0.4 m and 1.9 m. The standard deviations for the differences were 1.2–1.3 m.

Regression analysis was used to assess the effects of stand conditions and the laser scan angle on the stand height determined from the laser data. This analysis was related to two of the computed laser stand heights, namely the arithmetic mean height (h_{h1}) and the mean height computed according to the grid approach using a grid cell size of 15 × 15 m ($h_{15\times15}$).

First, the laser stand heights were regressed with h_L using a simple linear model. Since the bias of the laser height determination differed between sites, a dummy variable indicating the individual test sites was included. Thus, all 36 test stands from the two test sites were included in the same regressions. About 91% of the variation between the laser stand heights and the reference stand height was accounted

Table 4
Ground truth stand mean height regressed against laser mean height and various characteristics affecting the laser heights

Variable	Coefficient	
	laser height expressed by h_{hl}	laser height expressed by $h_{15\times15}$
Intercept	5.82 ***	3.98 *
h_{hl}	0.96 ***	
$h_{15\times15}$		0.75 ***
SITEDUMMY	−1.61 **	0.65 NS
G	0.078 *	0.061 NS
N	−0.0018 **	−0.0019 **
OFFNADIR	0.039 NS	0.046 NS
R^2	0.94	0.94

Level of significance: NS = not significant (>0.05); * = <0.05; ** = <0.01; *** = <0.001.

for. More complicated regressions were therefore applied in order to identify some of the sources of the remaining amount of variation. Models including several of the characteristics that might affect the laser heights were tried. However, the effects of characteristics such as tree species and vertical stand structure as expressed by the standard deviation between the field-measured tree heights within the individual stands were far from significant.

Table 4 presents two linear regressions with the following independent variables: (1) the laser heights, (2) a dummy variable indicating the individual test sites (SITEDUMMY), (3) stand density as expressed by basal area (G), (4) the number of trees per hectare (N), and (5) the off-nadir scan angle (OFFNADIR). F-tests showed that the simple regressions comprising only the laser heights and the dummy variable were not adequate when compared to the regressions in Table 4. The selected regressions accounted for 94% of the variation. Both regressions indicated a significant effect of N, and for stand density (G) a significant effect was found in one of the regressions. The estimated coefficients for the off-nadir scan angle were not significant.

4. Discussion and conclusions

The results of the current study revealed that the arithmetic mean of the laser heights seriously underestimated the ground truth mean height of the forest stands by 4.1–5.5 m (Table 3). However, such an underestimation seems to correspond to previous findings. For footprint diameters which probably were at least five times larger than those in the current experiment (Table 2), Aldred and Bonnor (1985) and Nilsson (1994) reported an underestimation of true mean height by 2.1–3.7 m using various profiling and scanning systems.

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 stand height estimates (Aldred and Bonnor, 1985). For practical forestry applications, however, it might be of interest to generate proper DEMs as well as estimating tree heights. Thus, there seems be to be a gap between laser data requirements for DEM generation and for tree height determination. Fortunately, certain remedies for bridging this gap seem to exist. The current analysis indicated that laser data with small footprint diameters might produce unbiased estimates of stand heights provided that only the largest laser values are selected. Therefore, the grid approach to hight determination seems promising. Nelson et al. (1988) showed that the largest ground-measured tree heights were better modelled by the three largest laser heights on a plot than by all the laser heights. For refining the grid approach, the effect of including the second and third largest laser values within each grid cell should be analyzed.

The grid approach seemed to affect the random errors in a positive manner too. For test site 1, the estimated standard deviation between laser mean height and ground truth mean height was reduced from 1.6 m for the arithmetic laser mean height to 1.3 m for the laser mean height determined by the grid approach (Table 3). The standard deviations of the current study were somewhat smaller than the standard deviation of 1.5–3.2 m reported by Aldred and Bonnor (1985) and Nilsson (1994). The standard deviations also seemed to be of the same magnitude, or even smaller than the standard deviation of 1.1–2.9 m reported from a dozen of Scandinavian studies on photogrammetric mean tree height determination of Norway spruce and Scotch pine stands (Næsset, 1996) and the standard deviation of 1.1–1.8 m found by photogrammetric measurements of the current test stands (Eid, 1996).

In Norway, determination of tree heights at the forest stand level is often carried out as part of large forest surveys, frequently covering about 100–500 km^2. Such stand-by-stand surveys 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 might provide an efficient means for stratified calibration of tree heights derived from laser measurements. The current regression analysis (Table 4) indicated that such stratification might be arranged according to, for example, stand density (basal area) and number of trees per hectare. Although the current material provided rather weak support for such recommendations in the statistical sense, it was found by Nelson et al. (1988) that the variation between laser-measured heights and ground-measured heights varied according to density.

In the present study, the tree species did not have any significant effect on the laser height determination. However, it has been reported that tree species may affect forest stand characteristics derived from laser measurements, such as tree heights (Nelson et al., 1988) and timber volume (Maclean and Krabill, 1986). 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 homogeneous way than the current material. Since the present analysis was based on a rather heterogeneous sample of stands regarding tree species composition, stand density, tree heights, etc. (Table 1), a stratified calibration of tree heights determined by laser measurements might provide more precise estimates of the true tree heights than indicated here.

Although the estimated coefficients for the off-nadir scan angle were not statistically significant (Table 4), the positive sign of the coefficients might be indicative of increased underestimation of the true stand height when measuring laser heights at an angle. Increasing the flying height and/or restricting the swath width would reduce the problems of off-nadir scanning. However, the exact effects of looking through the canopy at an angle need to be quantified, and the maximum scan angles that might be acceptable to specific applications need to be better determined.

The laser provided a widely scattered sample of laser measurements, and due to the small footprint diameters (Table 2) the laser covered only 0.2% of the area. The effect of area coverage on the tree height estimation was not treated in this study. Although Nilsson (1994) found that the most reliable estimates of tree heights for a footprint diameter of 0.8 m were obtained by an area coverage of about 7%, height determination according to the grid approach might be less affected by laser sample size than other approaches to tree height estimation as the grid approach utilizes the largest tree heights only. The tree height determination from laser measurements is affected by the footprint size too (Aldred and Bonnor, 1985; Nilsson, 1994). Suitable footprint diameters of 1.5–2.2 m have been suggested (Nilsson, 1994). It is likely, however, that height determination by the grid approach is less affected by footprint size than other methods. Nevertheless, the effects of e.g. sampling density and footprint size on various methods for tree height estimation need to be better examined in order to optimize the laser data collection.

The current study has shown that laser scanner data may be used to obtain estimates of forest stand heights with an accuracy equal to, or even higher than, those provided by present inventory methods based on aerial photo interpretation. It has also been shown that some kind of selection of the highest laser values seems to be required in order to avoid serious underestimation of the ground truth mean height. 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 height determination by laser scanning technology. It has been shown in the literature that at least laser profiling systems may be used to estimate other important forest resource attributes, such as timber volume (e.g. Maclean and Krabill, 1986). Only scanning systems might provide the required data basis for large-scale practical applications of laser data. Further research on extraction of forest characteristics should therefore be carried out with laser scanners properly calibrated for forestry applications.

Acknowledgements

This research was supported by the Norwegian Forest Trust Fund and the Norwegian Forest Owner Federation. I wish to thank Svein Søgnen, Øyvind Aase, and Ingrid Høydal for their kind support and for giving me the opportunity to use the laser scanner data collected by Fotonor AS, Norway, and TopScan GmbH, Germany. Thanks also to Tron Eid and Jarle Hamnes, who provided the field reference data.

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