# Detecting and Measuring Individual Trees Using an Airborne Laser Scanner

Åsa Persson, Johan Holmgren, and Ulf Söderman

## Abstract

*High-resolution airborne laser scanner data offer the possibility to detect and measure individual trees. In this study, an algorithm which estimated position, height, and crown diameter of individual trees was validated with field measurements. Because all the trees in this study were measured on the ground with high accuracy, their positions could be linked with laser measurements, making validation on an individual tree basis possible. In total, 71 percent of the trees were correctly detected using laser scanner data. Because a large portion of the undetected trees had a small stem diameter, 91 percent of the total stem volume was detected. Height and crown diameter of detected trees could be estimated with a root-mean-square error (RMSE) of 0.63 m and 0.61 m, respectively. Stem diameter was estimated, using laser measured tree height and crown diameter, with an RMSE of 3.8 cm. Different laser beam diameters (0.26 to 3.68 m) were also tested, the smallest beam size showing a better detection rate in dense forest. However, estimates of tree height and crown diameter were not affected much by different beam size.*

## Introduction

Airborne laser scanning systems now offer the possibility to retrieve three-dimensional information about individual trees. Airborne lidar systems were first used in profiling mode for estimating tree height and crown closure (e.g., Aldred and Bonner, 1985). Lidar-generated canopy profiles were used to estimate stem volume (Maclean and Krabill, 1986) with models similar to those earlier developed using aerial photographs mounted on a stereo plotter. Development of the Global Positioning System (GPS) and inertial navigation systems (INS) made it possible to determine the position of each laser reflection point with high accuracy. Scanning systems were developed, and Nilsson (1996) used the distance between the first and last peak of the returning pulse and the area of the waveform from a scanning system to estimate the stem volume on field plots. The vertical distributions for squares (typically 15 by 15 m) were used to estimate mean tree height and stem volume for forest management in previously mapped stands (Næsset, 1997a; Næsset, 1997b; Magnussen *et al.*, 1999).

As scanner technology has developed, the pulsing frequency of systems has increased rapidly. According to Ackermann (1999), it is possible to obtain up to 20 points per $m^2$ from an airplane at an altitude of 1000 m. Magnussen *et al.* (1999) states that six to ten laser hits per tree crown would be needed to detect individual trees. Samberg and Hyyppä (1999) have shown that individual trees can be identified using airborne laser data. Brandtberg (1999) detected individual trees using laser data and validated the results by comparing with aerial photographs. The ability to detect individual trees makes it possible to estimate the height and crown diameter of these trees. Using these estimates, the stem diameter and stem volume can be derived. The correlation between stem diameter and crown diameter was studied early in order to estimate stem diameter by measuring tree crown sizes in aerial photographs (e.g., Jakobsons, 1970).

Hyyppä *et al.* (2001) used laser-measured tree height and crown diameter to estimate the stem diameter of individual trees. Estimated stem diameter together with laser measured tree height was used as input to existing stem volume functions for individual trees, making it possible to estimate stem volumes for all detected trees in a stand. They evaluated the estimates using forest stands with a mean size of 1.2 ha and corrected for sampling error. Mean tree height and stem volume were estimated with a standard error of 9.9 percent and 10.5 percent of the mean values, respectively. These estimates were better than a traditional field inventory of the stands.

Detection of trees has usually been evaluated by comparison with aerial photographs, and estimates have been evaluated by summing values for all trees within delineated areas. In this study, evaluation of tree detection was possible because, at a test site in southern Sweden, the positions of all trees within delineated areas had been measured on the ground with high precision. An algorithm was first developed. The algorithm was evaluated over this area, and the ability to link field-measured trees with laser-measured trees made it possible to study which trees were detected. No parameter settings were changed during the evaluation. The measurement of tree height and crown diameter of the detected trees could also be evaluated. The effect of the beam size on these estimates was also possible to investigate because a laser scanning system with a programmable scanner was used. Furthermore, image processing methods for removal of penetration into the crowns based on theories of active contours (e.g., Cohen, 1991; Cohen and Cohen, 1993; Kass *et al.*, 1998) were evaluated for the first time.

The objectives of this study were to (1) evaluate how well individual trees could be detected by segmenting a canopy model of the tree crowns; (2) evaluate the accuracy of the tree height estimates, the crown diameter estimates, and the stem diameter estimates of the detected trees; and, finally (3), investigate the influence of the beam size on the ability to detect single trees and on the tree height and crown diameter measurements of individual trees.

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## Material

### Study Area

The study area was located in southern Sweden (lat. 58° 30′ N, long. 13° 40′ E). The dominating tree species were Norway spruce (*Picea abies L. Karst.*), Scots pine (*Pinus sylvestris L.*) and birch (*Betula spp.*). The area was essentially flat with a variation in elevation ranging from 120 to 145 meters above sea level.

### Laser Data

The laser data acquisition was performed on 13 September 2000 using TopEye, an airborne laser scanning system operated from a helicopter. The Laser Range Finder (LRF) measures the distance between the helicopter and the target up to 7000 times per second (Sterner, 1997). By combining sensor position data from the GPS and the INS, the altitude of the scanner, and distance measurements from the LRF, the system produced up to two geo-referenced *XYZ* positions for each laser sounding with an absolute accuracy of 0.10 to 0.30 m (Sterner, 1997). The pulsed laser (1064-nm) beam moves across the helicopter track controlled by the scanner and along track through the forward motion of the helicopter. The resulting pattern on the ground is thus Z-shaped. The post-processing system calculates the position of the reflecting object, the slant range, and the scanning angle. The position of the reflecting object is derived from the first and last peak of the returning pulse. Kinematic GPS was used with a base station placed in an open area within the measuring area. Laser measurements were made from five parallel flight lines in a north-south direction with a length of 2000 to 2500 m and a distance between the flight lines of 200 m. One flight was made for each flight line with each of the four beam divergences. The beam divergences were 1, 2, 4, and 8 mrad, giving a footprint diameter of 0.26 m, 0.52 m, 1.04 m, and 2.08 m, respectively. Flight altitude above ground was approximately 130 m, the speed 16 m/s, the scan mirror frequency 16.67 Hz, and the scan width ±20°. This gave a distance of 0.44 m between the laser hits on ground within a scan line and 0.48 m between scan lines in nadir. Data acquisition was also performed at a flight altitude of 230 m and with a beam divergence of 8 mrad to produce measurements with a footprint diameter of 3.68 m. All other settings were the same as for the lower altitude, giving a distance between the laser hits within a scan line of 0.79 m and distance between scan lines of 0.48 m.

### Field Data

Twelve rectangular field plots (50 by 20 m) were placed along the flight lines. The forest consisted mainly of middle and old aged spruce and pine. The dominating species (greater than 80 percent) were Norway spruce for six of the plots and Scots pine for six plots. Stem diameters of all trees (≥ 0.05 m stem diameter at 1.3 m above ground) within the plots were measured and the tree species were registered. The position of the center of these tree stems was measured (1.3 m above ground) relative to two reference points in the nearest open area for each plot using a total station. The outline of a plot within each stand was determined in the same way as the position of the individual trees. The positions of the reference points were measured using kinematic GPS equipment. According to the specifications for the GPS equipment, accuracies of 5 to 10 cm were possible to achieve. The same place was used for the base station as during the laser measurements. For a random sample of trees (≈15 within each plot), the height and crown diameter were measured. Tree heights were measured using an ultra-sound distance measurement and electronic angle decoder. The projected on-ground crown diameter was measured in the direction of the line of sight from the total station as specified by Jacobsons (1970). The position of the outermost part of the crown on both sides along the sightline was projected to the ground using a plumb line, and the distance on ground between these two points was then measured.

## Method

Laser height data were used to create a surface, recovering the tree crown contour, with local maxima that should have the positions of treetops. The laser beam has the characteristic of being able to penetrate the canopy of trees, and, therefore, ground hits will be obtained even in dense forest. This makes it possible to estimate the ground surface in dense forest that later can be subtracted from the tree crown surface. However, penetration into the tree crowns causes large height variations within individual tree crowns, making it difficult to separate tree crowns from each other. Therefore, penetrations were removed by creating a surface following the outer part of the crowns. Height variation, left after penetration removal and caused by branches, was removed by smoothing. Because the tree size is not known in advance and varies within the forest, the smoothing scale cannot be determined *a priori*. Therefore, the fact that tree crowns are radially symmetric was used and a parabolic surface was fitted to the elevation data. The best fit determined an appropriate scale in different parts of the image.

The method of identifying individual trees and estimating the height and crown diameter of these trees consisted of six parts:

(1) first, a digital surface model (DSM) was created,
(2) a digital terrain model (DTM) was created,
(3) the canopy of the trees was modeled and a digital canopy model (DCM) was created,
(4) the DCM was smoothed with different scales,
(5) a parabolic surface was fitted to the elevation data to determine which scale to choose for different parts of the image, and finally
(6) the height and crown diameter were estimated for the identified trees (Persson, 2001).

### Creating a DSM from Laser Data

The laser data covering the field plots were selected. The unevenly distributed laser reflection points were converted into two raster layers with a cell size of 1/3 m. The first raster layer was assigned the height value of the lowest laser reflection point within each cell. This raster layer was referred to as $DSM_{min}$. The second raster layer was assigned the highest laser reflection point within each cell. This raster layer was referred to as $DSM_{max}$ (Figure 1a). If a cell contained no laser reflection point, the value of this cell was determined by averaging the height values found in the eight neighboring cells.

### Creating a DTM from Laser Data

The $DSM_{min}$ was used to estimate the ground level. The DTM was created using active contours implemented in an algorithm created by Elmqvist (2000) (Figure 1b). The contour can be seen as a net being pushed upward from underneath the surface and attached to the laser measurement points.

The shape of the active contour depends on the properties of the contour together with the surrounding image. Elmqvist (2000) made several simplifications compared with general active contours. The net was only allowed to move along the *Z*-axis. This makes it possible to describe the contour with an image matrix containing only height values. The internal energy depends only on the elasticity of the contour. The internal energy in a node is a summation of the elasticity forces between the node and its eight connected neighbors. The elasticity force between a node and a neighbor point is the arc tan function. The force field around one image point only exists on the *Z*-axis. The attraction force in an image point is a Gaussian function. The start position of the net is below the lowest laser point. To help the net raise towards the ground, an external force is applied in the initial stage. The forces are calculated in each

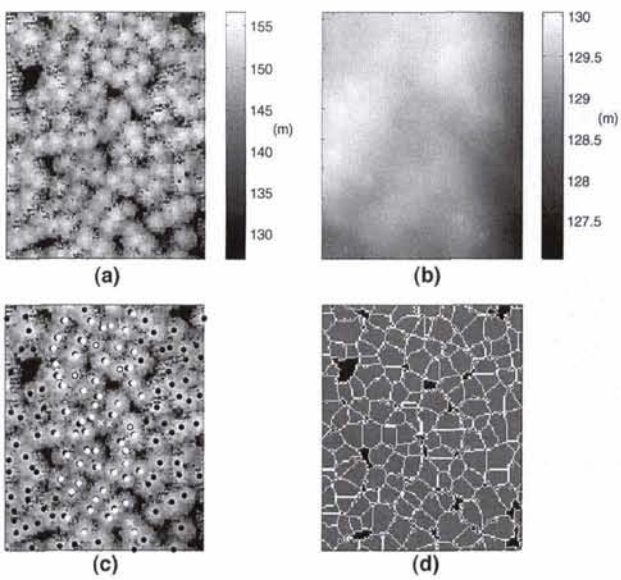


Figure 1. (a) Digital surface model ($DSM_{max}$). (b) Digital terrain model (DTM). (c) Laser-measured and field-measured positions of trees. Black dots represent laser-measured positions of treetops, white dots represent field-measured stem positions, black circles with white dots represent laser-measured and field-measured positions at the same pixel, and white crosses represent field-measured trees that were not detected by the laser. (d) Segmentation of tree crowns.

node in the net and the net is updated. This procedure is repeated until the net converges towards a solution with a tolerance that has been set. When the net has converged, the external force is turned off and iterations are continued until the net converges again.

#### Creating a Digital Canopy Model (DCM)

For lowpass filtering the surface, one would like to use a surface describing the canopy of the trees and not include pixels where pulses have penetrated the foliage and hit the ground or within the tree. To remove the pulses that had penetrated the vegetation, the same active contour algorithm that was used to estimate the ground level was applied from above so that the active contour surface (ACS) followed the outer part of the crowns (Figure 2a). The difference between the digital surface model ($DSM_{max}$) and the digital terrain model (DTM) was then calculated and the resulting image was thresholded at 2 m. To avoid that pixels that were close to a tree were assigned values of the ACS that were interpolated between the tree crown and the ground, the thresholded image was median filtered (5 by 5). Pixels that were zero after applying the median filter were assumed to belong to the ground with no tree coverage and the ACS was set to zero at these pixels. Pixel values where the height difference between the ACS and the original laser height was greater than 2 m were replaced by the value of the ACS (Figure 2b). Thus, pulses that hit below the canopy were removed, which resulted in less variation in height within single trees.

#### Smoothing the Tree Canopy

To smooth the surface and make it more likely that each tree has a single height maxima, a 2D Gaussian filter was used (Equation 1), where $x$ and $y$ is the distance to the kernel center. The smoothing operation was performed with three different $\sigma$ settings, $4/\pi$, $6/\pi$, and $8/\pi$.

$$G(x, y) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2+y^2}{2\sigma^2}} \quad [1]$$

The location of the trees was estimated by searching for local height maxima in the smoothed images. Seeds were placed out in every pixel more than 2 m above the ground surface and allowed to climb in the direction having the largest slope. When a seed reached a position where all neighboring pixels had lower values, a local maximum was found. The crown coverage was estimated by grouping those pixels that climbed to the same maximum, and these pixels defined a segment. The smoothing of the coarsest scale ($\sigma = 8/\pi$) was chosen so that in general no tree had more than one maximum. The finest scale ($\sigma = 4/\pi$) was chosen so that most trees were detected with the effect that some of the larger trees would have more than one maximum.

#### Combination of Scales

To determine which scale to choose in different parts of the image, a second-order parabolic surface (Equation 2) was fitted to the height data of the top 30 percent of the segment using the DCM: i.e.,

$$z = a(x - x_0)^2 + b(y - y_0)^2 + c \quad [2]$$

where $x$, $y$ is the pixel location and $x_0$, $y_0$ is the center of the surface.

Three different cases could occur when comparing the segmented areas of trees from a coarser scale with the corresponding area from a finer scale: (1) the finer scale could also have only one maximum, (2) the finer scale had detected more than one maximum within a tree, and (3) the finer scales had detected more than one maximum because the coarser scale had merged trees. For case (1), the top was taken as correctly determined. For cases (2) and (3), the problem was to determine if additional maxima at the finer scales should be judged as separate trees or as belonging to the treetop detected with the coarser scale. The parabolic surface was used with the center ($x_0$, $y_0$) placed at the maximum that was found in the coarser scale. Each additional maxima in the finer scale was tested starting with the closest to ($x_0$, $y_0$). The surface was first fitted to the segment at the finer scale that belonged to the maximum ($x_0$, $y_0$) and the segment of the additional treetop being tested at the finer scale by minimizing the sum of residuals: i.e.,

$$min\ \delta = \sum_i (z_i - z)^2 \quad [3]$$

The surface was then fitted with the center placed at the same position but now using only the segment from the finer scale that belonged to the maximum that was detected in the coarser scale. If the sum of residuals decreased by more than a set threshold (8 percent) at the pixels where the parabolic surfaces overlapped, the treetop only found in the finer scale was judged as a separate treetop. This procedure was first performed with the coarsest scale ($\sigma = 8/\pi$) and the middle scale ($\sigma = 6/\pi$). The resulting segments were then compared with the finest scale ($\sigma = 4/\pi$). Figure 1 shows estimated positions of trees (black marks) (Figure 1c) and the crown coverage (Figure 1d) when a combination of scales was used.

#### Estimation of Tree Height, Crown Diameter, Stem Diameter, and Stem Volume

For each segment, the maximum laser height value above the ground surface was chosen as the measure of the tree height (*laser_height*). The area of the segments was used to calculate the crown diameter (*laser_diameter*) as if the tree crown had the shape of a circle. The stem diameter (*stem_diameter*) was predicted using both the *laser_height* and *laser_diameter*: i.e.,

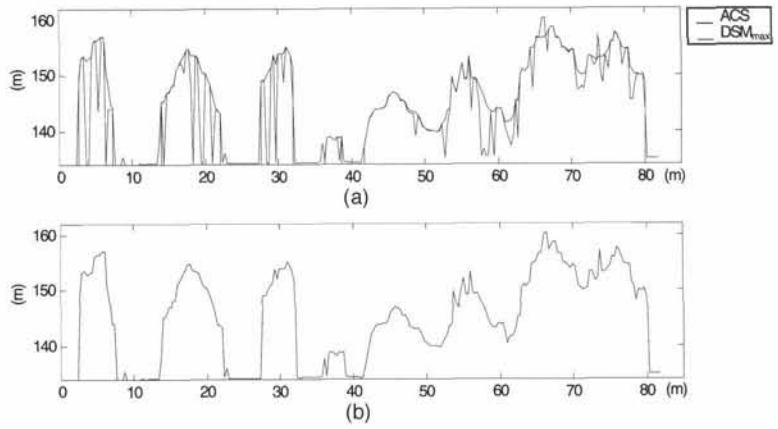


Figure 2. (a) Cross-section of active contour surface applied from above. (b) Digital canopy model (DCM).

$$stem\_diameter = b_0 + b_1 \times laser\_height \times laser\_diameter + \varepsilon. \quad [4]$$

The stem volume was calculated for the trees using volume functions (Näslund, 1947) with the *stem_diameter* and *laser_height* as variables.

#### Evaluation Method

To evaluate the results, each detected tree was linked to the corresponding field tree. For each segment, three different cases could occur: (1) no field tree was within the segment, (2) one field tree was within the segment, and (3) more than one field tree were within the segment. For case (1), the segment was judged as a segment that had no field tree. For case (2), the field tree was linked to the laser-detected tree. For case (3), the field tree that was closest to the position of laser-detected tree was linked to the tree. When the laser trees and the field trees had been linked with the rules above, each field tree that had not been linked was examined. For each of these trees, a search was done at a maximum distance of two pixels in all directions. If a segment was found that had not been linked and it was within the field plot, the field tree was linked to this segment. If a tree was not detected in the laser data, typically a small tree next to a large tree, this smaller field-measured tree was sometimes linked to a detected tree if positioned closer than the correct taller field-measured tree. This error in linking could be found by comparing the field-measured and laser-measured tree height of linked sample trees. In order to remove incorrectly linked trees, trees where the laser-measured height was twice the field-measured height (seven trees) were excluded from the dataset. The ability to link the trees made it possible to study how well individual trees can be detected. Furthermore, the laser-estimated height, crown diameter, stem diameter, and stem volume of the detected trees were compared with the field measurements. Also, because different beam sizes were used, their effect on the ability to detect individual trees and on the estimates was studied.

## Results

#### Number of Detected Trees

The automatically extracted trees using the smallest beam size were compared with the field-measured trees. In Figure 1c, the white marks show the positions of the field trees (a white dot indicates that the tree has been detected and linked, and a white x-mark that the tree has not been identified). Out of the 795 trees, 562 (71 percent) were detected (Table 1). Two false detections were found. Small trees in between tall trees are not likely to be detected (Figure 3). Most of the large trees were detected (Table 1).

This is also illustrated in Figure 4 where the distribution of stem diameters for the trees on the different plots is shown. The trees are sorted in ascending order according to the stem diameter. Trees that were not detected have been marked with a black circle. Four types of forests are represented; (1) low and dense pine forest (plot 6), (2) two-layered pine forest (plots 2, 4, and 5), (3) one-layered pine forest (plots 1 and 3), and (4) spruce forest (plots 7, 8, 9, 10, 11, and 12). A large portion of the undetected trees had a small stem diameter.

Because most of the undetected trees were small, they did not contribute much to the total stem volume. The stem volume of the detected portion of the trees was compared with the stem volume of all trees. The stem volume of each tree was calculated using the stem diameter and tree height (Näslund, 1947). For the detected portion of trees, both the laser-estimated and the field-measured stem diameter and tree height were used to calculate the stem volume. These volumes were compared with the volume of all trees calculated using field measurements. Over all plots, the laser-estimated volume of the detected trees was 89 percent of the total volume and the field-estimated volume was 91 percent of the total volume (Table 1).

The positional differences between linked laser-measured and field-measured trees are shown in Figure 5. The center of the pixel was defined as the position of the detected trees. The average positional difference of the stem positions was 0.51 m. The position of the center of the stem 1.3 m above ground was measured in the field and the position of the treetop was measured by the laser scanning.

#### Estimation of Tree Height

In Figure 6, laser-estimated tree height is plotted against field-measured tree height for sample trees. The line fitted to the data using the least-squares method had an intercept of 1.13 m, a slope of 1.00, and an RMSE of 0.63 m. The correlation coefficient was 0.99.

#### Estimation of Crown Diameter

Figure 7 shows laser-estimated crown diameter plotted against field-measured crown diameter for sample trees. The line

TABLE 1. PORTION OF DETECTED TREES FOR DIFFERENT STEM DIAMETERS AND THE TOTAL STEM VOLUME CALCULATED USING THE FIELD DATA (TOTAL VOLUME), THE VOLUME OF THE DETECTED TREES CALCULATED USING THE FIELD DATA (DETECTED VOLUME), AND THE VOLUME OF THE TREES DETECTED CALCULATED USING THE LASER MEASUREMENTS (ESTIMATED VOLUME) ARE SHOWN

| Plot | Number of Trees (≥ 5.0cm) | Detected Trees with a Stem Diameter | | | | Stem Volume ($m^3$) | | |
|---|---|---|---|---|---|---|---|---|
| | | ≥ 5.0cm | >10.0cm | >15.0cm | >20.0cm | Estimated Volume | Detected Volume | Total Volume |
| 1 | 28 | 96% | 96% | 96% | 96% | 46 | 39 | 39 |
| 2 | 63 | 49% | 50% | 61% | 69% | 40 | 42 | 55 |
| 3 | 31 | 87% | 96% | 96% | 96% | 24 | 25 | 25 |
| 4 | 73 | 62% | 93% | 93% | 93% | 28 | 24 | 26 |
| 5 | 64 | 67% | 89% | 93% | 93% | 31 | 27 | 29 |
| 6 | 143 | 41% | 54% | 70% | 89% | 10 | 12 | 19 |
| 7 | 55 | 76% | 78% | 82% | 89% | 45 | 51 | 57 |
| 8 | 48 | 77% | 77% | 78% | 85% | 41 | 43 | 46 |
| 9 | 61 | 85% | 85% | 87% | 86% | 58 | 54 | 59 |
| 10 | 101 | 85% | 86% | 89% | 98% | 34 | 34 | 37 |
| 11 | 66 | 83% | 83% | 85% | 87% | 43 | 59 | 64 |
| 12 | 62 | 95% | 95% | 95% | 97% | 51 | 51 | 52 |
| total | 795 | 562 (71%) | 549/694 (79%) | 531/621 (86%) | 471/522 (90%) | 451 (89%) | 461 (91%) | 508 |

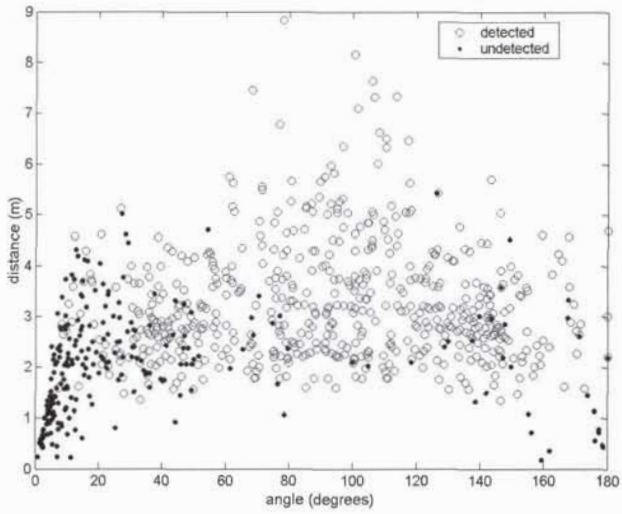


Figure 3. Characteristics of detected and undetected trees. The distance (m) is the distance to the closest detected tree and angle (degrees) is the vertical angle from the treetop between zenith and the treetop of the closest detected tree.

fitted to the data using the least-squares method had an intercept of 1.40 m, a slope of 0.74, and an RMSE of 0.61 m. The correlation coefficient was 0.76.

#### Estimation of Stem Diameter and Stem Volume

The field-measured stem diameter was compared with the product of the laser-measured crown diameter and laser-measured tree height (Figure 8) for sample trees. The linear model gave an RMSE of 3.8 cm, corresponding to 10 percent of the mean value. Also, the stem volume of each sample tree, calculated using the laser-estimated tree height and stem diameter, was plotted against the stem volume calculated using the field-measured tree height and stem diameter (Figure 9). The RMSE of the volume estimates was 0.21 $m^3$, corresponding to 22 percent of the mean value.

#### Influence of the Beam Size

In Table 2, the effect of the beam size on the ability to detect individual trees is illustrated. The smallest beam size was slightly more efficient for finding individual trees (66 percent compared to 71 percent). The laser measurements of the trees that were detected with all laser beam sizes were compared. The measurements of the height and the crown diameter were not affected much by the beam size (Table 3). The largest beam size gave more underestimation of the tree height.

## Discussion

The results demonstrate the ability to detect individual trees using laser scanner data of high resolution with an algorithm that recovers the outer contour of the tree crowns. Four types of forests were represented in the validation data set: (1) low and dense pine forest, (2) two-layered pine forest, (3) one-layered pine forest, and (4) spruce forest. The highest detection rate was found in type 3 forests, where almost all trees were detected. The second highest detection rate was found in type 4 forests, with most undetected trees with small diameters. The third highest detection rate was found in type 2 forests, with almost all undetected trees in the lower tree layer consisting of small deciduous trees together with small and suppressed spruce trees. The lowest detection rate was found in the dense and low pine forest (type 1). For optimization of forest operations, the portion that was detected is the most important. This portion contains most of the valuable timber and is subject to decisions about thinning or final felling.

Undetected treetops usually have a small vertical angle from zenith to the nearest detected treetop and a short horizontal distance to the nearest detected tree. For example, plot 6 consisted of low and dense pine forest where many trees had less than a meter between the stems and were thus not visible from the height data and not detected. Small trees that were not linked correctly can explain the fact that some of the undetected trees in Figure 3 have an angle close to 180 degrees. A much taller tree that should have been linked instead of a small tree will result in a large angle.

The accuracy of the tree height estimates (RMSE = 0.63 m) is comparable to the accuracy of the measurements achieved from the ground. The standard error for *Suunto* hypsometer measurements varies from 0.4 to 0.8 m (Lindgren, 1984). If one assumes that measurements with the electronic hypsometer used in this study had the same standard error, a significant portion of the RMSE could be caused by the error in field data. Hyypää *et al.* (2000) validated tree height measurements from a high resolution airborne laser scanning system in Finland. The linear regression for deriving field-measured height from laser-measured height (89 trees) gave a standard error of 0.97 m,

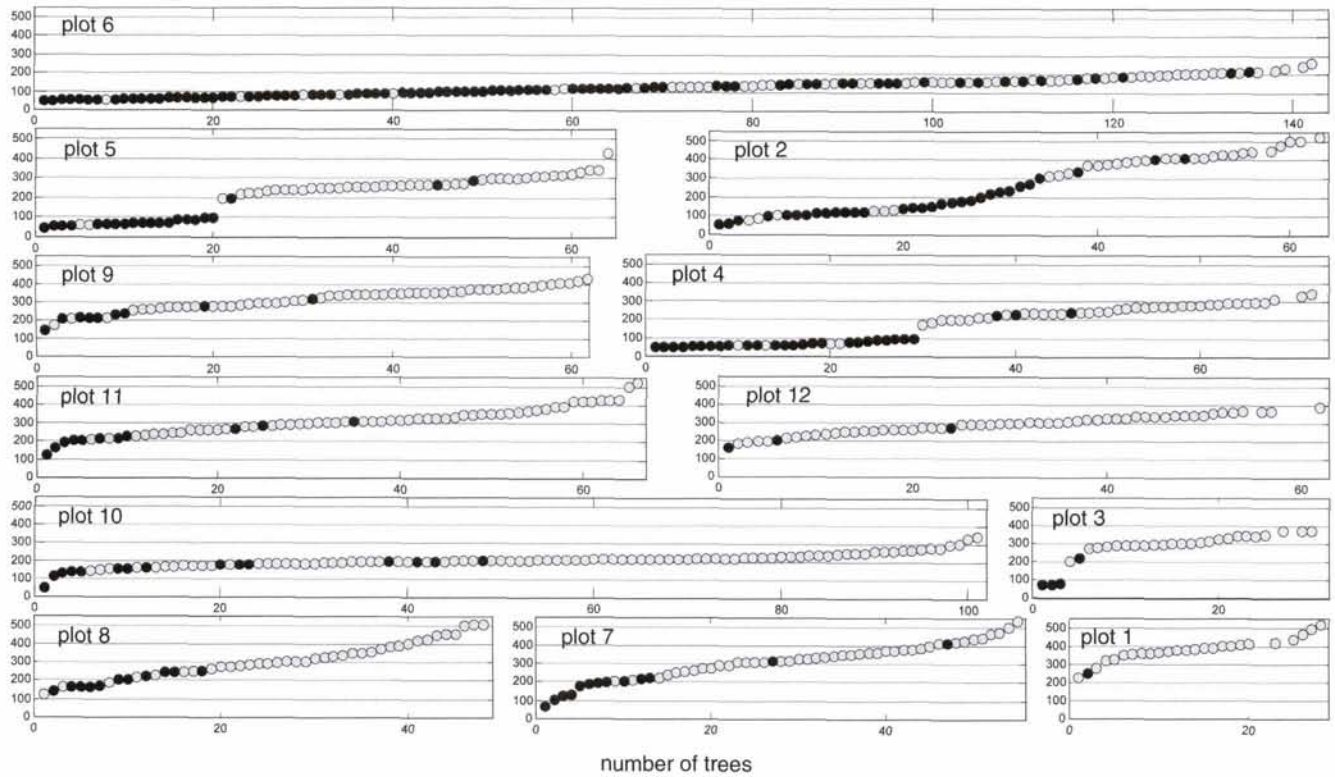


Figure 4. Cumulative distribution functions of tree sizes (stem diameter (mm)) of laser-detected trees (open circles) and non-detected trees (filled circles).

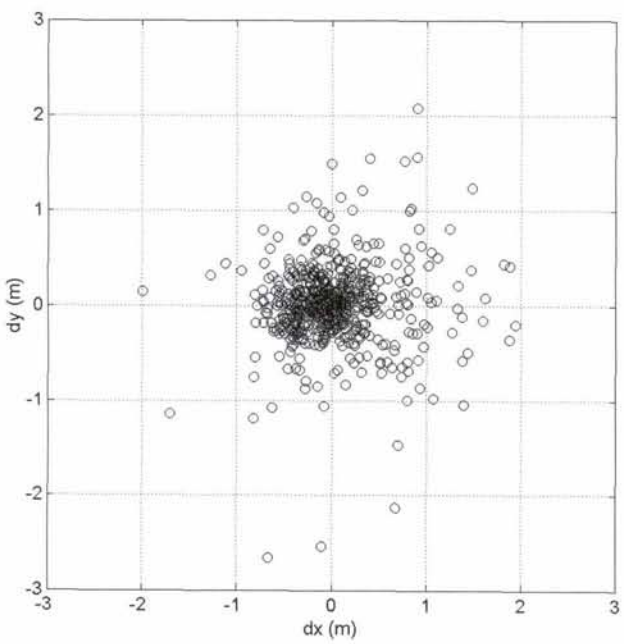


Figure 5. Positional differences of estimated stem positions relative to field-measured stem positions.

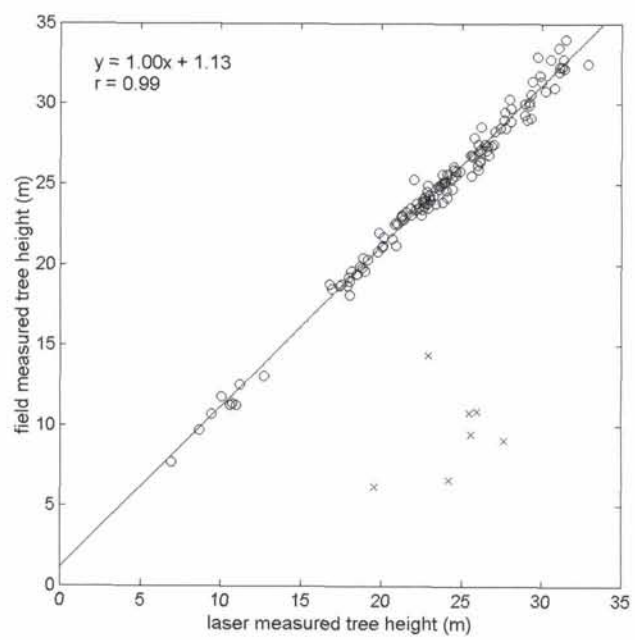


Figure 6. Estimated height of sample trees plotted against field measurements, 135 trees. X-marks show the incorrectly linked trees.

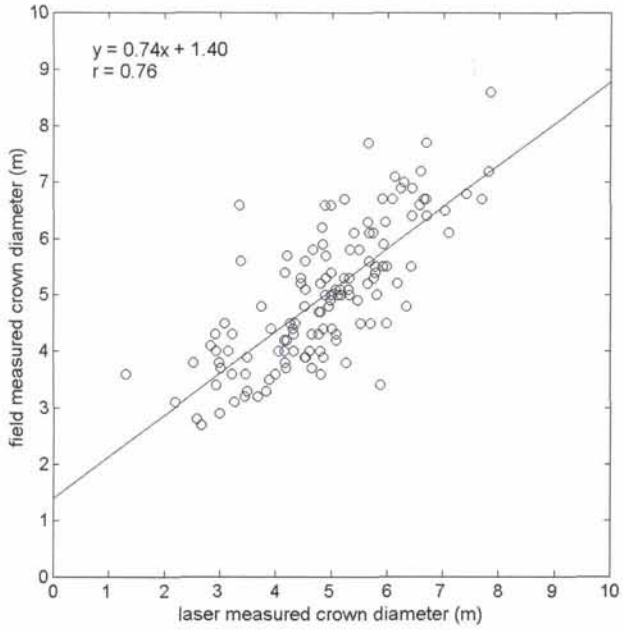


Figure 7. Estimated crown diameter of sample trees plotted against field measurements, 135 trees.

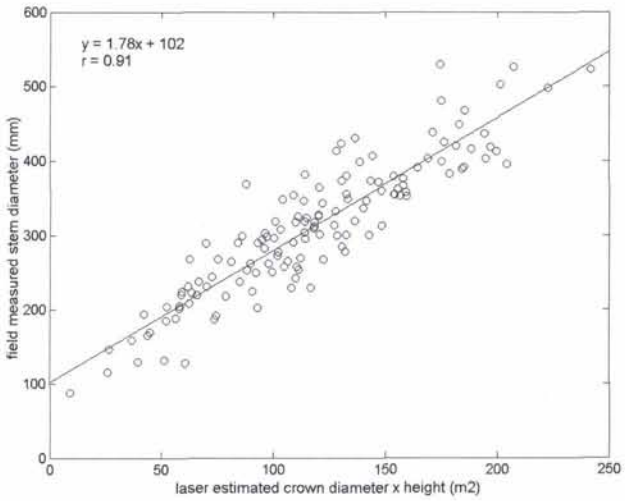


Figure 8. Field-measured stem diameter of the sample trees plotted against laser-measured crown diameter times laser-measured tree height, 135 trees.

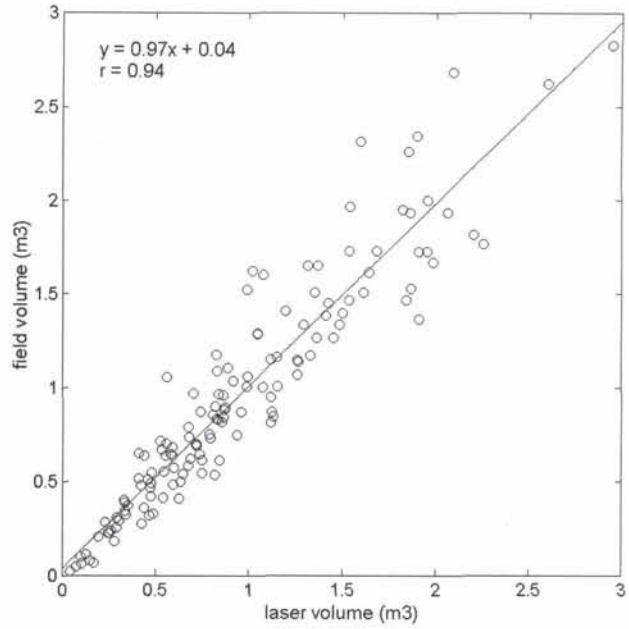


Figure 9. Field-measured stem volume plotted against laser-measured stem volume of the sample trees, 135 trees.

TABLE 2. NUMBER OF DETECTED TREES FOR DIFFERENT BEAM SIZES

| Plot | Footprint Diameter (m) 0.26 | 0.52 | 1.04 | 2.08 | 3.68 | Actual Number of Trees |
|---|---|---|---|---|---|---|
| 1 | 27 | 27 | 27 | 27 | 27 | 28 |
| 2 | 31 | 32 | 32 | 32 | 32 | 63 |
| 3 | 27 | 28 | 28 | 26 | 29 | 31 |
| 4 | 45 | 45 | 44 | 45 | 42 | 73 |
| 5 | 43 | 43 | 43 | 42 | 43 | 64 |
| 6 | 58 | 59 | 54 | 54 | 47 | 143 |
| 7 | 42 | 40 | 41 | 39 | 38 | 55 |
| 8 | 37 | 36 | 37 | 37 | 35 | 48 |
| 9 | 52 | 53 | 53 | 52 | 52 | 61 |
| 10 | 86 | 81 | 85 | 78 | 75 | 101 |
| 11 | 55 | 54 | 53 | 54 | 53 | 66 |
| 12 | 59 | 59 | 59 | 57 | 55 | 62 |
| Total | 562 (71%) | 557 (70%) | 556 (70%) | 543 (68%) | 528 (66%) | 795 |

TABLE 3. RELATION BETWEEN FIELD-MEASURED AND LASER-MEASURED TREE HEIGHT AND CROWN DIAMETER FOR DIFFERENT BEAM SIZES

| Footprint Diameter (m) | Height (m) Intercept | Slope | RMSE | Crown Diameter (m) Intercept | Slope | RMSE |
|---|---|---|---|---|---|---|
| 0.26 | 1.11 | 1.00 | 0.65 | 1.30 | 0.76 | 0.78 |
| 0.52 | 1.20 | 1.00 | 0.72 | 1.10 | 0.79 | 0.77 |
| 1.04 | 1.42 | 0.99 | 0.64 | 1.20 | 0.78 | 0.75 |
| 2.08 | 1.13 | 1.01 | 0.64 | 1.55 | 0.70 | 0.77 |
| 3.68 | 1.66 | 1.00 | 0.76 | 1.74 | 0.68 | 0.82 |

similar to that which was achieved in this study, but bias was much lower (0.14 m). The low bias in the Finnish study could be caused by the extremely high resolution (24 measurements/$m^2$), making it more likely that the uppermost part of the treetop was hit.

Some portion of the error of the crown diameter could be explained by the sampling error given due to only measuring from one side. Because the segmentation technique does not allow segments to overlap, the method will assign too small a diameter for trees with intersecting tree crowns. Areas of non-detected trees will be added to surrounding trees, resulting in too large a diameter for some trees.

The same type of sampling error as for the field measurements of the crown diameter is introduced when measuring stem diameters from only one direction because the stem not is absolutely circular. Stem diameter cannot be measured directly from laser scanner data, but the correlation between stem

diameter and crown diameter multiplied by tree height can be used for stem diameter estimates. Thus, stem diameter and tree height can be determined for all detected trees in a forest. The possibility to retrieve this information in an effective way makes it possible to optimize forest operation to a degree that earlier has not been possible. Only a set of field-measured trees to calibrate the laser measurements is needed, and then the laser measurement of all trees covered by the laser scanner can be used. The results in this study indicated that this calibration is not much affected by the beam divergence.

The techniques for estimation of forest variables that were developed before the resolution of laser data was high enough to detect individual trees are still of interest even if high-resolution data can be collected. All trees cannot be detected, especially in young dense forests where trees grow extremely close together (e.g., 0.1 m) or in multi-layered parts of forests. Individual tree crowns cannot be recovered for these trees but the laser data still reveals the vertical distribution of vegetation. Therefore, techniques to detect and measure single trees need to be combined with other techniques that do not rely on individual tree detection.

## Conclusions

Using airborne laser scanner data, single trees can be detected and forest parameters on an individual tree basis can be derived. The probability that a tree is detected depends on its distance to the closest tree and the relative height of this tree. The detection rate was 71 percent of all trees (≥ 5 cm stem diameter) in the plots. Because most large trees were detected, 91 percent of the stem volume was found. Tall trees are more valuable than small trees, so it is likely that the detected portion contains 90 to 100 percent of the timber value. The error of tree height measurements of the detected sample trees (0.63 m) and crown diameter (0.61 m) is comparable with the measurement error achieved by manual field measurements but can be done much more efficiently with regard to time. Stem diameter of the detected trees can be estimated using the laser-measured tree height and crown diameter. The error is of course higher compared to manual measurements but is still only 10 percent of the mean value. The smallest laser beam diameter (0.26 m) was more effective for detecting trees when there was a short distance between the trees. Measurements of tree height and crown diameter were not affected much by different beam sizes of the laser. All laser measurements were done with a low scanning angle (0 to 5 degrees). The effect of the scanning angle needs to be studied if higher scanning angles are to be used. Only the height data was used in this study. More information is delivered from the laser scanning system. Use of intensity data and type of return pulse (single or multiple) might be useful for deriving information of the trees. Results in this study demonstrate the usefulness of airborne laser scanning data for forest monitoring and management.

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## References

Ackermann, F., 1999. Airborne laser scanning - Present status and future expectations, *ISPRS Journal of Photogrammetry & Remote Sensing*, 54:64–67.

Aldred, A.H., and G.M. Bonner, 1985. *Application of airborne laser to forest surveys*, Report PI-X-51, Canadian Forest Service, Canada, 62 p.

Brandtberg, T., 1999. *Automatic Individual Tree-Based Analysis of High Spatial Resolution Remotely Sensed Data*, doctoral thesis, Acta Universitatis Agriculturae Sueciae, Silvestria 118, Swedish University of Agricultural Sciences, Uppsala, Sweden, 155 p.

Cohen, L.D., 1991. On active contour models and balloons, *Computer Vision, Graphics, and Image Processing*, 53:211–218.

Cohen, L.D., and I. Cohen, 1993. Finite element methods for active contour models and balloons for 2D and 3D images, *IEEE Transaction on Pattern Analysis and Machine Intelligence*, PAMI-15(11):1131–1147.

Elmqvist, M., 2000. *Automatic Ground Modeling Using Laser Radar Data*, Masters Thesis LiTH-ISY-EX-3061, Department of Electrical Engineering, Linköping University, Linköping, Sweden, 30 p.

Hyyppä, J., U. Pyysalo, H. Hyyppä, and A. Samberg, 2000. Elevation accuracy of laser scanning-derived digital terrain and target models in forest environment, *Proceedings of the 4th EARSeL Workshop on LIDAR Remote Sensing of Land and Sea*, 16–17 June, Dresden, Germany, pp. 139–147.

Hyyppä, J., O. Kelle, M. Lehikoinen, and M. Inkinen, 2001. A segmentation-based method to retrieve stem volume estimates from 3-D tree height models produced by laser scanners, *IEEE Transaction on Geoscience and Remote Sensing*, 39(5):969–975.

Jakobsons, A., 1970. *The Correlation between the Diameter of the Tree Crown and other Tree Factors — Mainly the Breast-Height Diameter. Analysis Based on Sample Trees from the National Forest Survey*, Report 14, Department of Forest Survey, Royal College of Forestry, Stockholm, Sweden, 75 p.

Kass, M., A. Witkin, and D. Terzopoulos, 1998. Snakes: Active contour models, *International Journal of Computer Vision*, 1:321–331.

Lindgren, O., 1984. *A Study of Circular Plot Sampling of Swedish Forest Compartments*, Report 11, Section of Forest Mensuration and Management, Swedish University of Agricultural Sciences, Umeå, Sweden, 153 p.

Maclean, G.A., and W.B. Krabill, 1986. Gross-merchantable timber volume estimation using airborne LIDAR system, *Canadian Journal of Remote Sensing*, 12:7–18.

Magnussen, S., P. Eggermonth, and V. La Riccia, 1999. Recovering tree heights from airborne laser scanner data, *Forest Science*, 45:407–422.

Næsset, E., 1997a. Estimating timber volume of forest stands using airborne laser scanner data, *Remote Sensing of Environment*, 61:246–253.

———, 1997b. Determination of mean tree height of forest stands using airborne laser scanner data, *ISPRS Journal of Photogrammetry and Remote Sensing*, 52:49–56.

Näslund, M., 1947. *Functions and Tables for Computing the Cubic Volume of Standing Trees: Pine, Spruce and Birch in Southern Sweden and in the Whole of Sweden*, Report 36, National Forest Research Institute, Stockholm, Sweden, 81 p.

Nilsson, M., 1996. Estimation of tree heights and stand volume using an airborne LIDAR system, *Remote Sensing of Environment*, 56:1–7.

Persson, Å., 2001. *Extraction of Individual Trees Using Laser Radar Data*, Masters Thesis EX013, Chalmers University of Technology, Göteborg, Sweden, 28 p.

Samberg, A., and J. Hyyppä, 1999. Assessing tree attributes from the laser scanner data: The high-scan case, *Proceedings of the Fourth International Airborne Remote Sensing Conference and Exhibition*, 21–24 June, Ottawa, Ontario, Canada, 21:251–258.

Sterner, H., 1997. Helicopter aerial laser ranging, *Proceedings of the 3rd EARSEeL Workshop on LIDAR Remote Sensing of Land and Sea*, 17–19 July, Tallinn, Estonia, pp. 113–118.

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