

## DETECTING AND ESTIMATING ATTRIBUTES FOR SINGLE TREES USING LASER SCANNER

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### ABSTRACT

*This paper demonstrates extensively for the first time that high-pulse-rate laser scanners are capable to detect single trees in boreal forest zone, and characteristics of single trees, such as height, location, and crown dimensions can be determined providing accurate standwise estimates for stem volume and mean height. In the boreal forest zone and in many forest areas, there exists gaps between the forest crowns. For example, in Finland, more than 30 % of the first pulse data reflect directly from the ground without any interaction with the canopy. By increasing the number of pulses, it is possible to have samples from each individual tree and also from the gaps between the trees. Basically this means that several laser pulses can be recorded per m<sup>2</sup>. This allows detailed investigation of forest areas and the creation of a 3-dimensional tree height model. Tree height model can be calculated from the digital terrain and crown models both obtained with the laser scanner data. By analysing the 3-dimensional tree height model by using image vision methods, e.g. segmentation, it is possible to locate individual trees, estimate individual tree heights, crown area and, by using that data, to derive the stem diameter, number of stems, basal area and stem volume. The advantage of the method is the capability to measure directly physical dimensions from the trees and use that information to calculate the needed stand attributes. It is shown that tree heights of individual trees in the dominating storey can be obtained with less than 1 m standard error. In addition, the following standard errors were obtained for mean height, basal area and stem volume at stand level: 2.3 m (13.6 %), 1.9 m<sup>2</sup>/ha (9.6 %), and 16.5 m<sup>3</sup>/ha (9.5 %), respectively. The accuracy was better than the accuracy of conventional standwise field inventory.*

### 1. INTRODUCTION

The small-area forest inventory is typically carried out by manual work, aerial photo interpretation, photogrammetric measurements, and growth models. However, first three of the methods are time-intensive, laborious, and expensive. Typical costs per hectare are 15-20 ECU, of which about 50-60 % is used for data acquisition and recording - tasks that can be substituted by remote sensing. However, these time-intensive and laborious methods have been the only possibilities for getting accurate data for small-area forest inventory. Satellite images, e.g. Landsat and Spot images, have been used in multi-source forest inventory giving rather reliable estimates for forest attributes in areas of larger than 100 hectares. Stand attributes at stand level (1-3 hectares in size) have been interpreted visually from high-resolution aerial images, and proven to be time-consuming and quite sensitive to systematic error (Anttila, 1998). The rapid development of computer-related techniques has enabled the introduction of semi-automated forest inventory based on delineation of single tree crowns. Several authors have achieved promising results (Uuttera et al., 1998, Brandtberg and Walter, 1998; Dralle and Rudemo, 1996; Geougeon, 1997). The semi-automated inventory is cost-effective and it can be used for many purposes, especially when combined with field measurements. However, although semi-automatic inventory methods have been developed mainly using aerial photographs and video images, the obtained accuracy has not been adequate for detailed standwise inventory. Therefore, the search and development for more powerful data sources has been carried out.

Since many of the stand attributes are related to the height of the canopy, vertical canopy profiling is another potential solution to the problem. Hegershoff (1939) presented the concept of producing stand profiles (cross-sections of forest canopy) as early as in 1939. He introduced the use of stand profiles for preparing stand aerial volume tables. It was not until in the 80's when automatic profiles were taken, first with a laser and then with a radar. Nelson et al. (1984, 1988) demonstrated that the elements of the stand profile are linearly related to crown closure and may be used to assess the tree height, stem volume and biomass. Hyyppä (1993) demonstrated that the ranging radar is a powerful tool for determining the mean and dominant tree height, total basal area, stem volume, height of the crown base and classification of categorical variables of stands, such as development classes, land classes, bog types and fertility classes. Several papers have confirmed the capability of profiling measurements in the tree height and stem volume or biomass estimation. These earlier studies were based on vertical canopy probing and the applied instruments were not capable to measure anything but the forest under the flight line. Despite this, better performance of the non-scanning profiling radar over aerial photographs and imaging spectrometer demonstrated by Hyyppä et al. (1999a) suggests a good potential of profiling sensors for forest inventory. Promising results concerning the quality of laser scanner data for forest inventory was reported by Hyyppä et al. (1999b). Later study by Hyyppä and Hyyppä (2000a) compared laser scanner-derived stand attribute estimates with corresponding interpretations using other optical remote sensing data sources and found the laser-derived predictors more informative for forest inventory than the use of predictors of e.g. imaging spectrometer AISA.

Recently, the application of laser scanners to forestry have been demonstrated (Nässet, 1997) and a European-wide project (HIGH-SCAN) to demonstrate its usefulness for forest inventory at the stand level has been launched (Hyyppä, 1998). The laser scanners are capable to record a digital 3-dimensional surface model of targets. These systems can provide spatial resolutions of better than 1 m to be used to detect individual tree crowns.

Previously, it has been found that the disadvantages of laser for forest inventory include limited penetration and ground detection capability through vegetation and reduced probability to detect treetops (since the laser beam is typically very narrow) (Nelson et al., 1984, 1988). However, the situation changes when the number of pulses transmitted by the laser scanner increases. In the boreal forest zone and in many forest areas, there exist gaps between the forest crowns. For example in Finland, roughly speaking more than 30 % of the first pulse data reflects directly from the ground without any interaction with the canopy. By increasing the number of pulses, it is possible to have samples from each individual tree and also from the gaps between the trees. Basically this means that several laser pulses can be recorder per m<sup>2</sup>. This allows a detailed investigation of forest areas and the creation of 3-dimensional tree height map. As explained above, the tree height map can be calculated from the digital terrain and crown models, both obtained with the laser scanner data. By analysing the 3-dimensional tree height model by using image vision methods, it is possible to locate individual trees, estimate individual tree heights, crown area and derive using that data stem diameter, number of stems, basal area and stem volume. The advantage of the method is the capability to measure directly fysical dimensions from the trees and use that information to calculate the needed stand attributes.

This paper will demonstrate extensively for the first time that the above mentioned approach gives high accuracy results for standwise forest inventory. The paper will concentrate on how the 3-dimensional tree height model can be obtained and how the stand attributes can be calculated from the single tree data. The quality of the results will be tested by statistical analysis.

## 2. DATA ACQUISITION

### 2.1 Test site

The boreal test site (Kalkkinen) is located in southern Finland, 130 km north of Helsinki. From a larger forest area, an intensive area of 100 hectares (2-km-by-0.5-km) was selected for the study. The test site is rather hilly and situates about 110 m above sea level. The main tree species are Norway spruce and Scots pine whereas the mean stand size is 1.2 hectares.

### 2.2 Field inventory

In the forest inventory on stand level, the forest area studied is first delineated into homogeneous forest units, namely forest stands, typically 1 to 3 hectares in size. Important forest characteristics, including the stem volume per hectare, are then assessed to these stands by measuring sample plots and individual trees and by using personal experience. Forest attributes at stand level are then calculated on the basis of these sample plots and using ocular estimation. Typically, required stand attributes include stem volume per hectare, mean height, basal area per hectare, tree species information, age, development class and description of ground vegetation. From these data, treatment proposals are then planned. The most valuable attribute for the forest inventory is the stem volume, which should be assessed with an error of less than 15 %.

**Standwise field data.** Conventional stand-wise forest inventory was carried out on August-October 1996 according to the procedure depicted above, using sample plots and personal experience. From these data, mean tree height [m], basal area [ $\text{m}^2/\text{ha}$ ], and stem volume per hectare [ $\text{m}^3/\text{ha}$ ] were obtained for each stand basically as means of the sample plot values. In order to monitor the cutting activity and other changes occurring between autumns 1996 and 1998 (laser acquisition), aerial photograph was taken in parallel with the field inventory and laser campaign. Changes were monitored visually and changed stands were rejected from further analysis. The descriptive statistics of the stand attributes information used for analysis are shown in Table 1 (41 stands).

**Table 1. Descriptive statistics of the field inventory data**

<i>Character</i>	<i>Mean height</i>	<i>Basal area</i>	<i>Volume</i>
Mean value	16.9 m	19.3 $\text{m}^2/\text{ha}$	174.7 $\text{m}^3/\text{ha}$
Standard deviation	7.0 m	10.5 $\text{m}^2/\text{ha}$	115.4 $\text{m}^3/\text{ha}$
Minimum value	3.0 m	0.3 $\text{m}^2/\text{ha}$	1.0 $\text{m}^3/\text{ha}$
Maximum value	24.2 m	34.3 $\text{m}^2/\text{ha}$	361.4 $\text{m}^3/\text{ha}$

**Treewise measurements.** A systematic sample plot network with 100-m spacing was designed for the test site. The location of center of each sample plot was determined with an accuracy of better than 1 m using advanced GPS/GLONASS system by Finnish Road Administration. From each plot (Figure 1), basal area with stratification by species, diameter and tree species of each tree, height and age (of at least 3 trees of every species and stratum) was measured. From every 5<sup>th</sup> plot, the location, diameter at breast height (1.3 m) and height of every tree were recorded. The location of every tree was measured as a reference to the center of the sample plot. Distance and angle deviating from compass north were recorded. From this data 89 trees were used for verification of single tree height estimation and 25 trees were used to derive the ratio between the crown area and stem diameter.

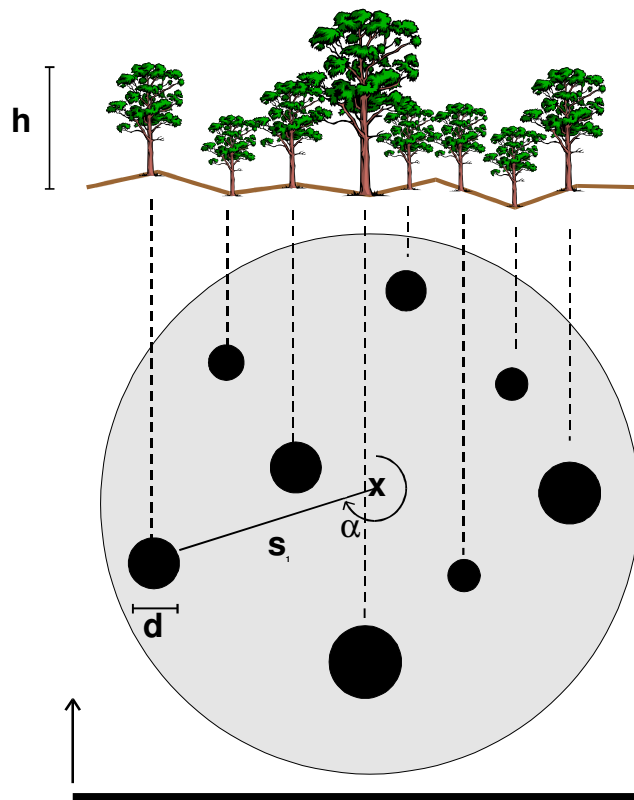


Figure 1. From every 5<sup>th</sup> plot, the location, diameter at breast height (1.3 m) and height of every tree were recorded. The location of every tree was measured as a reference to the center of the sample plot. Distance and angle deviating from compass north were recorded.

### 2.3 Laser scanning

Laser scanning is based on distance measurements and precise orientation of these measurements between a sensor (the position of which is well known) and a reflecting object (the position to be defined). By knowing the sensor position, the distance and the incidence angle of each measurement, one can easily calculate the co-ordinates of the reflecting object. The scanning mechanism sweeps the laser beam across the flight line providing coverage across the flight track. Along track coverage is provided by the aircraft's motion. By using sensitive and noise-suppressing kinematic DGPS receivers, the position of the sensor can be measured with an accuracy of about 0.1 m. Further, a corresponding reference station must be placed within or close to the surface area. Sensor's orientation is obtained with a better accuracy than 0.2. This results in accuracy better than 1 m in x- and y-directions. With respect to the reference plane, each measured point can then be characterized by three co-ordinates (x, y, z). The detailed measurement principle of laser scanning over forested areas is depicted in Figure 2.

Concerning forest inventory, measurement density, incidence angle, and capability to obtain the profile information requires careful validation. High measurement density is required in order to be able to detect individual tree crowns. Steep incidence angle enables to have sufficient number of ground hits. Test flights (TopoSys, 1996) have shown that at incidence angles of more than 10° off-nadir, the amount of shadowed areas heavily increases, i.e., the number of measured ground hits decreases and gaps in the DEM occur more frequently. The profiling capability is typically limited in laser scanners to few modes. Typically both the first and the last pulse are included; referring to the first and last echoes of distributed targets, such as the forest.

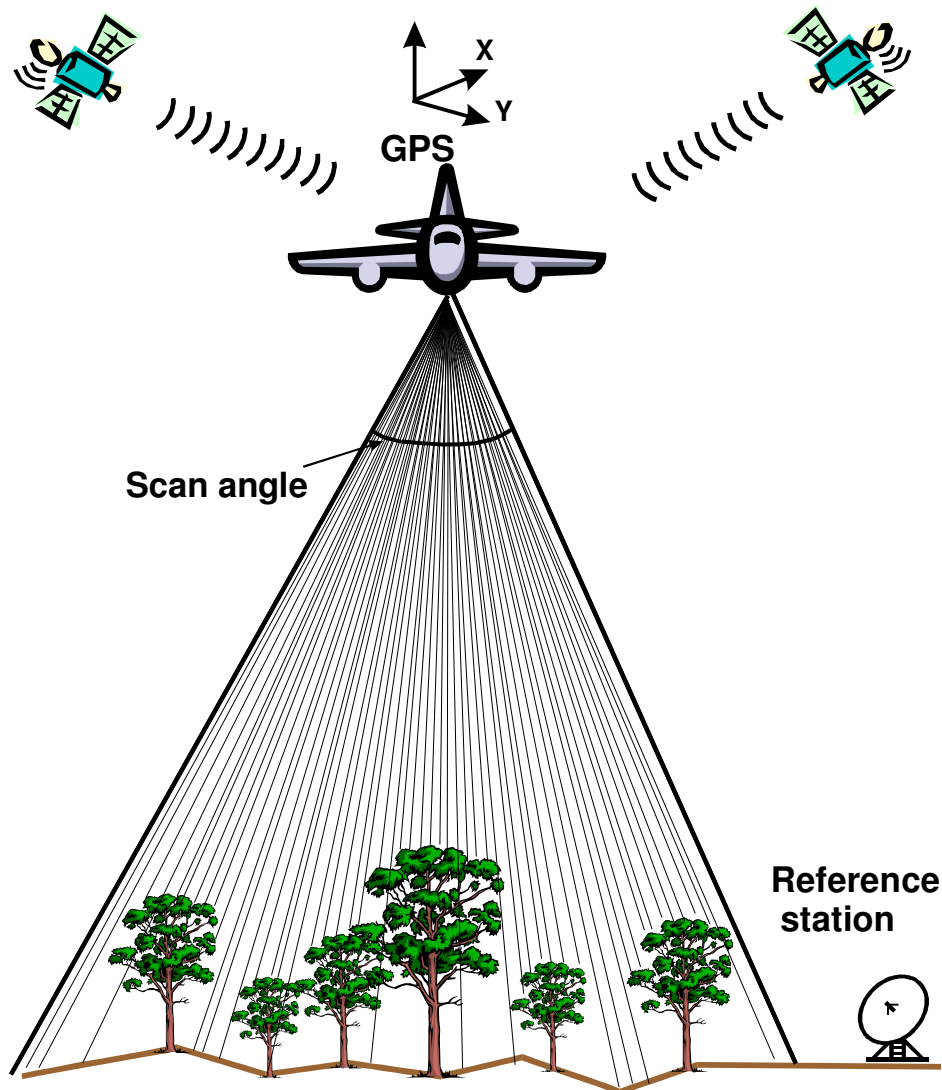


Figure 2. The measurement principle of laser scanner for forest assessment.

There are a small number of the airborne laser scanners available on the market today. Main providers are TopoSys, Optech and Saab Survey Systems. TopoSys laser scanner was selected for the study due to its high measurement density and steep incidence angle. The performance of the TopoSys-1 laser is depicted in Table 2.

The laser scanner campaign was carried out on 2-3 September 1998. TopoSys-1 laser scanner was installed in the local aircraft. Three DGPS receivers were employed to record the carrying platform position: one on board the aircraft, and two ground reference GPS stations (the first as basic receiver, the second for backup). The 2-by-0-5-km test site was intensively flown from the altitude of 400 m resulting in measurement density equivalent of more than 10 measurements per  $m^2$ . The survey altitude was selected in order to guarantee the number of pulses needed to separate individual trees. Due to the survey altitude applied, the swath width was approximately 100 m. Both the first and last pulse modes were collected.

**Table 2. TopoSys-1 laser scanner performance parameters.**

<i>Parameter</i>	<i>Performance(s)</i>
Sensor	pulse-modulated, TopoSys-1
Laser pulse frequency	83 000 Hz
Scan frequency	630 Hz
Field of View	$\pm 7.1$ degrees
Measurement density	4...5 per m <sup>2</sup> at 800 m
The number of shots per scan	128 parallel shots (one of which is the reference)
Swath width at 800 m	200 m
Position accuracy	x,y < 1.0 m
Elevation accuracy WGS84)	z < 0.15 m
Laser classification	class 1 by EN 60825 (eye-safe)

### 3. PREPROCESSING OF LASER DATA

The data was calibrated with the calibration flight from cross-tracks over the Kalkkinen area. As a result of the calibration, correction angles of  $-0.03^\circ$  in pitch and of  $-0.08^\circ$  in roll were applied. The captured data of the flights were transformed into the Finnish co-ordinate system KKK-3. The systematic errors occurred in the transformation were corrected using ground control points of summer cottages, road junctions and the base map.

Laser scanner survey provided a cloud of points, the x, y and z coordinates of which are known. They form a digital surface model (DSM), which includes terrain points, vegetation points, and points reflected from buildings. By processing the data and classifying the points to terrain and vegetation points, it was possible to produce digital terrain model (DTM) and digital vegetation model (DVM). When only the top of the vegetation is included in the model, it can be called digital crown model (DCM). The difference between the DCM and DTM models is called in this study a digital tree height model (DTHM), 3-dimensional representation of the tree heights within the target forest area.

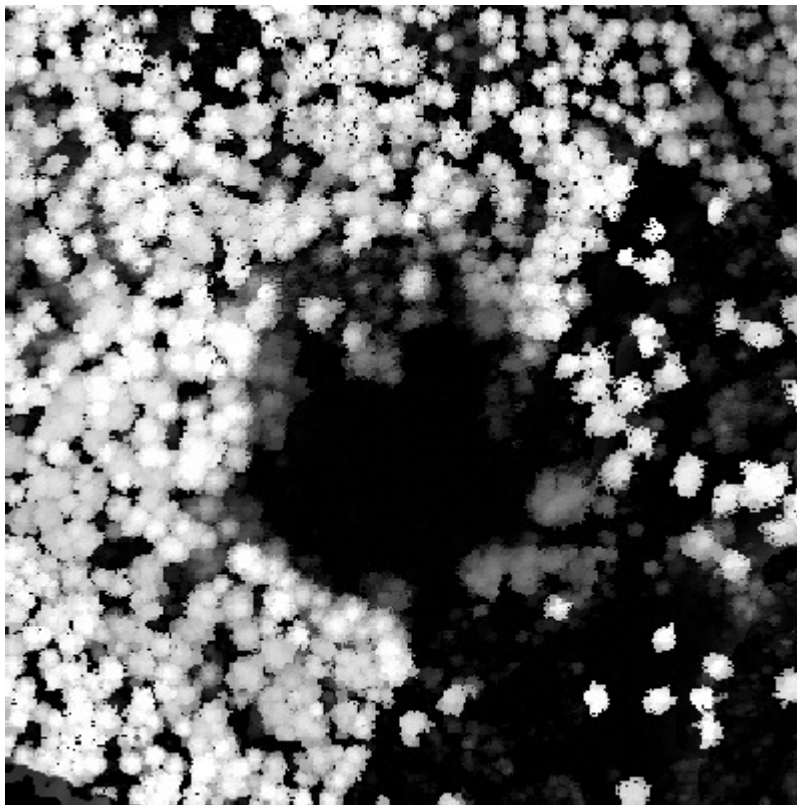
There may exist several ways of producing the DTHM, but the developed procedure is given here. First, the cloud of x, y and z co-ordinates is transformed into a grid. When individual tree crowns are assessed, a requested resolution is about 50 cm requiring about 10 laser-based samples per m<sup>2</sup>. The grid was calculated by simply selecting the laser hits related to certain (x,y) pair. A simple but efficient mechanism to start the DCM and DTM conversions is to select the maximum and minimum z values within each pixel (x,y) corresponding to maximum and minimum surfaces. The maximum surface represents rather well treetops and ground when there is no tree cover above the ground. When there are holes (no data), the value for these points can be obtained by interpolation and using the knowledge of nearby pixels. Diverging points can be detected by gradient method and thresholding. The minimum surface was further used for the DTM generation. Since many trees were still visible in the minimum surface, an 8-by-8 m filter removing the existing crown hits was designed mainly looking for the minimum values. That surface was then used to classify the original data into ground hits ( $g_i$ ) and crown hits ( $c_i$ ). If the pixel value of the minimum surface deviated less than a certain threshold (0.5 m or 1 m) from the filtered minimum surface, the pixel was assumed as the ground hit. Using the ground hits, other values in the surface were interpolated using Delaunay triangulation. The interpolation did not change the values of these ground hits.

The new surface was then to be used as a new reference (substituting filtered minimum surface) and new classification could be done. The iteration can be continued, until the new classification does not alter enough number of ground hits. Typically 3 to 4 iteration steps are needed at maximum.

The final DTHM was calculated as the difference between the DCM and the DTM. The demonstration was carried out using first pulse data since it appeared that the first pulse mode was enough to provide the needed information. The use of the both modes would be likely to further improve the results obtained in this paper.

Figure 3 shows the obtained DTHM for a sample area. No iteration was done in order to produce the DTM and DTHM. As a threshold value, 1 m offset was applied for classification and linear fitting together with the Delaunay triangulation.

During the segmentation process, tree crown shape and location of individual trees were determined. Trees were found by looking at the local maxima in the laser-derived tree height model. Before the maxima finding, tree height model was low-pass-filtered. Without any filtering, the amount of tree crowns is typically too high. Too much filtering causes oversize for the tree crowns (undersegmentation). The tree crown segments were determined by the modified watershed segmentation procedure. The segmentation algorithm was originally developed for aerial photos and video images. The segmentation method is described in detail in (Hyypä et al., 2000). Figure 4 depicts an example output of the segmentation process.



*Figure 3. Obtained digital tree height model for a sample area.*

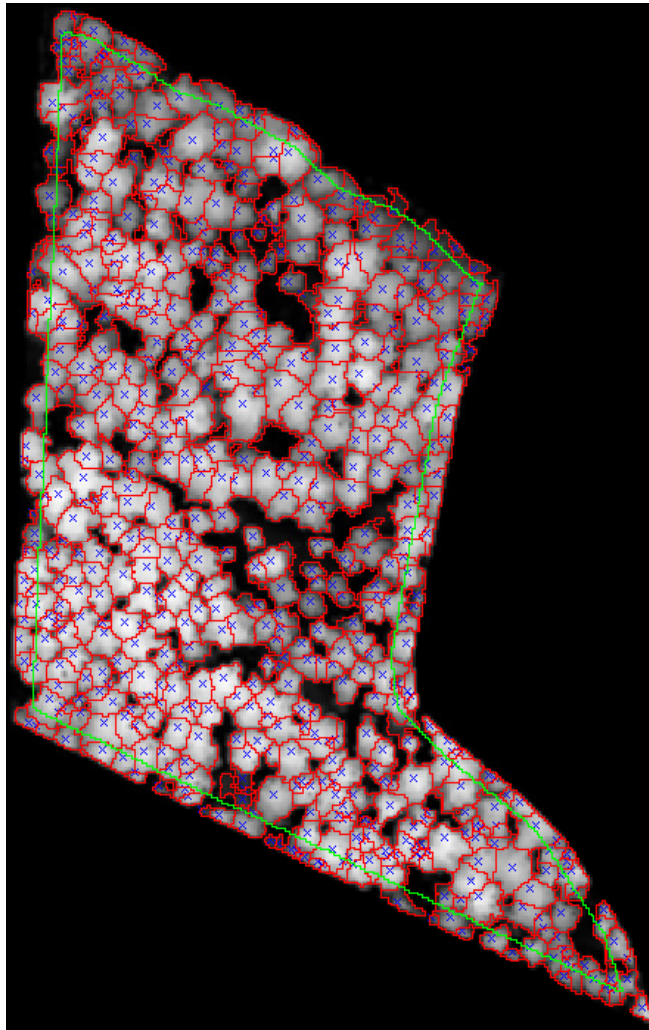


Figure 4. Segmentation output for a sample area.

#### 4. STAND ATTRIBUTES ESTIMATION

The calculations of the stand characteristic estimates for a single stand is based on the measurement of the location, tree height and tree crowns areas for each single tree. From that information all other stand characteristics are derived.

##### 4.1. Treewise attributes

The location of the tree can is determined by the location corresponding to maximum tree height of each tree segment.

The height of the tree  $h$  is the maximum value of tree height model within that segment.

$$h = \max(h_i), \quad (1)$$

where  $h_i$  are individual tree heights of digital tree height model within the corresponding segment area.

The crown diameter can be calculated using the segmented crown area  $A$  information as follows

$$L = \sqrt{\frac{4A}{\pi}} \quad (2)$$

In the boreal forest zone, there exists a correlation between the crown diameters and the breast height diameter  $d$  for each tree species (Ilvessalo, 1950). Ilvessalo measured 2815 trees of Scots pine and found a correlation of 0.77 between stem diameter and crown diameter. Stratification into 2-m height classes improved the correlation as high as 0.85 for some of the height classes. Norway spruce had correlation coefficients between 0.39 and 0.55 for different height classes. The corresponding range for birch was between 0.64 and 0.79.

Since no reliable tree species classification was carried out using either laser scanner data or aerial images, an average model relating stem diameter and crown diameter was formed. Since the height correlates strongly with stem diameter and height can be assessed accurately with laser scanner (Hyypä et al., 1999b), the following regression formula was derived

$$d = \alpha L + \beta h + \gamma \quad (3)$$

where coefficients  $\alpha, \beta$  and  $\gamma$  were calibrated using local field inventory data.

The basal area of the single tree ( $\text{m}^2/\text{ha}$ )  $g$  is

$$g = \frac{\pi}{4} d^2 \quad (4)$$

The stem volume ( $\text{m}^3/\text{ha}$ ) of single tree were obtained by Laasasenaho's formulas (Laasasenaho, 1982) in which volume is estimated using stem diameter  $d$  and height of the tree  $h$ . The formulas are derived for each tree species (birch, pine and spruce).

$$\text{Pine} \quad v = 0.036089 d^{2.01395} (0.99676)^d h^{2.07025} (h-1.3)^{-1.07209} \quad (5)$$

$$\text{Spruce} \quad v = 0.022927 d^{1.91505} (0.99146)^d h^{2.82541} (h-1.3)^{-1.53547} \quad (6)$$

$$\text{Birch} \quad v = 0.011197 d^{2.10253} (0.986)^d h^{3.98519} (h-1.3)^{-2.65900} \quad (7)$$

The standard errors of the models are 7-8,5 % (Laasasenaho, 1982).

If the tree species information is not derived, the arithmetic average or weighted average (with probabilities of each tree species) of calculated volumes should be used. In this study, the models for different tree species were weighted by 1/3.

#### 4.2 Standwise attributes

Standwise estimates were defined by calculating single tree attributes within the specified area. Since standwise estimates are typically expressed in units per hectare, a coefficient  $S$  relating the stand values to hectare-wise values had to be formed

$$S = \frac{10000}{R}, \quad (8)$$

where  $R$  is the area (in square meters) specified by the stand boundaries.

Standwise volume  $V$  [m<sup>3</sup>/ha], basal area  $BA$  [m<sup>2</sup>/ha] and mean height  $H$  [m] were expressed as

$$V = \sum_i v_i S \quad (9)$$

$$BA = \sum_i g_i S \quad (10)$$

$$H = \frac{\sum_i h_i w_i}{\sum_i g_i} \quad (11)$$

The mean height was calculated as Lorey's mean height; weighted by basal area of each tree.

The number of stems  $N$  [pc/ha] were correspondingly

$$N = \max(i)S, \quad (12)$$

where the function  $\max(i)$  gives the number of stems within the stand area.

## 5. EVALUATION METHOD

The above mentioned methods (Sections 3 to 4) were implemented in Matlab environment and the segmentation program was obtained from Arboreal Oy. As an input to the segmentation procedure, a 0.5-m resolution tree height model was created using the TopoSys-1 laser scanner data obtained during the Finnish campaign. The parameters of the segmentation algorithm were fixed before the processing of the test, and same parameters were applied for all stands selected. Therefore, the method was applied in an automatic manner.

The formula (3) relating stem diameter and tree height was calibrated by using 25 crown, stem diameter and height measurements. The correlation coefficient of the formula was 0.65 and standard error 4.4 cm. The use of several tree species within the same model deteriorated the performance.

In order to evaluate the accuracy of single tree height measurement, the treewise field inventory data was imported to image processing system together with the digital tree height model. The coordinates of the each tree were calculated to the same coordinate system. The field-measured tree and laser-derived tree were matched by finding the laser-derived tree location with the smallest deviation from field measured tree location. 89 trees could be found deviating less than 1.5 m from the field-measured value.

In order to evaluate the accuracy of the segmentation-based single tree estimation methods applied to standwise forest inventory, mean squared error (abbreviated to MSE), was calculated.

$$MSE = \sum_{i=1}^n (e_{1i} - e_{2i})^2 / (n-1) \quad (13)$$

where  $e_{1i}$  is the result obtained with the described laser-based method for stand  $i$ ,  $e_{2i}$  is the corresponding field-measured value, and  $n$  is the number of stands.

As a reference material for standwise estimation, conventional forest inventory depicted in Section 2 was applied. Since accuracy of the conventional forest inventory affects on the evaluation, the accuracy of conventional inventory was assessed and the errors due to inaccuracy of the field inventory were removed from the mean squared errors. Since these two errors can be assumed as independent, the corrected root mean squared error were expressed as

$$RMSE = \sqrt{MSE - \frac{1}{l} \sum_{i=1}^l Var(\delta_i)}, \quad (14)$$

where  $Var(\delta_i)$  refers to variance of conventional field inventory error  $\delta_i$  for stand  $i$ . The accuracy of field inventory measurement was verified in earlier study (Hyypä et al., 1999a) by measuring carefully 40 stands in near-by area (unfortunately laser mission could not cover them) spending one man-day to each stand. These intensive checking were performed by measuring about 10 relascope sample plots in each stand. Tree species and the diameter at breast height (dbh) were recorded for each measured tree, determined with a relascope factor of 1. Age, diameter at breast height, and height were measured for the basal-area-median-tree of each sample plot. From these data, mean tree height (m), basal area ( $m^2/ha$ ), and stem volume per hectare ( $m^3/ha$ ) were obtained for each stand basically as means of the sample plot values. The accuracy of the intensive stands could be calculated from the variance of the plot data. Comparing that data against the conventional field inventory data and taking into account the internal variance of the intensive checking, the standard error of the conventional inventory was obtained. The systematic error of conventional field inventory was obtained by assuming that there is no bias in intensive field checking.

The RMSE was divided into two parts, systematic error  $x$  and standard error of the estimate  $s$  as derived from

$$x = \sum_{i=1}^n (e_{1i} - e_{2i}) / (n - 1) \quad (15)$$

$$s = \sqrt{RMSE^2 - x^2} \quad (16)$$

Coefficient of determination,  $R^2$ , was obtained by dividing the sum of squared standard error explained by the method by the sum of squared errors explained by the average (SSEA)

$$R^2 = \frac{SSEA - s^2}{SSEA} \quad (17)$$

## 6. RESULTS AND DISCUSSION

Figure 5 shows the regression plot for the derivation of individual tree heights from laser scanner data. The 89 selected trees were mainly from the dominating storey. Individual trees were measured with an accuracy better than 1.0 meters using scanning laser data. The bias with respect to hypsometer measurements was 14 cm. The coefficient of determination was 0.97. The result implies that no single or dominant tree was missed by the laser. Previously, Hyypä et al. (1999b) reported a corresponding accuracy of 1.5 m. The improvement can be explained by the modifications in DTM generation and improvements in the selection of the corresponding tree from the laser data. The accuracy of conventional clinometer measurements is typically better than 0.5 m but for taller trees (>25 m) can be up to 1 m.

Therefore, the obtained accuracy seems to be incredibly promising for operational activities. In evaluation of usability of the results, one has to take into account, that the time spent for manual height measurements is enormous; and with the laser, the height of all trees could be assessed within a fraction of time, but the flying time of laser survey is still expensive. However, the cost per tree of laser surveys are just a fraction of that of manual measurements but the measured trees can be more qualitatively selected in field surveys.

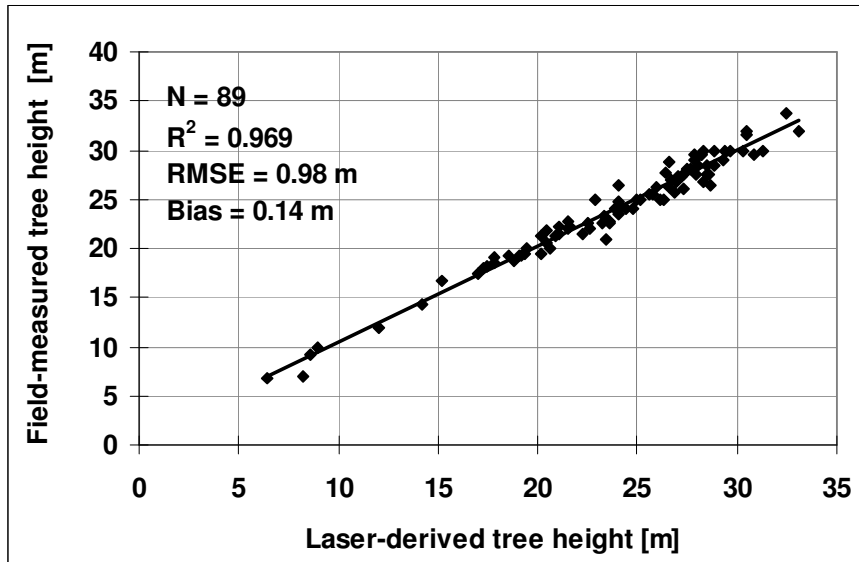


Figure 5. Laser-derived tree heights compared to field-measured tree heights of individual trees.

Table 3 summarizes the results obtained for 41 stands. The estimated accuracy of field inventory is better than reported in (Hyypä et al. 1999a) since the stand size of the applied material is higher than that used in (Hyypä et al. 1999a). The effect of stand size was corrected according to results reported by Hyypä and Hyypä (2000b). The scatterplots between the laser-derived and field-measured estimates are depicted in Figure 6.

**Table 3. Summary of the accuracy estimation.**

<i>Data Source/Error</i>	<i>Mean height</i>	<i>Basal Area</i>	<i>Volume</i>
Field inventory/Standard error	1.7 m	3.0 m <sup>2</sup> /ha	35.8 m <sup>3</sup> /ha
Field Inventory/Systematic error	+0.57 m	0.0 m <sup>2</sup> /ha	+19.3 m <sup>3</sup> /ha
Laser scanner/Standard error	2.3 m	1.9 m <sup>2</sup> /ha	16.5 m <sup>3</sup> /ha
Laser scanner/Standard error-%	13.6 %	9.6 %	9.5 %
Laser scanner/Systematic error	+ 2.5 m	- 9.7 m <sup>2</sup> /ha	- 65 m <sup>3</sup> /ha

The mean tree height was obtained with 2.3 m standard error (conventional field inventory 1.7 m). The overestimation can be explained that laser scanner is capable to detect only the trees that can be seen above the and also due to growth of 2 years. Since the height of each tree in dominant storey can be assessed with 1 m accuracy, the standard error 2.3 m is most likely due to errors in field inventory that were not taking properly into account when calculating the corrected mean squared error and errors due to improper use of the segmentation algorithm (very dense forests). Examples of both are results obtained for sapling and young stands. Even though laser overestimated these stands, there was one stand differing more than 9 m from average behavior (field inventory giving too low estimate). Since it has been found in

this study and in previous study (Hyypä et al. 1999b) than laser does not miss trees in dominant layer using as high pulse rate and low flying altitude as in this study, it is most likely that there has been severe field inventory error in this stand. This conclusion was confirmed by new field visit. Additionally it seems that the use of same parameters for all stands in the segmentation procedure was not justified. Since the tree height values given as input for the segmentation algorithm are absolute and not relative tree heights, either the method should be revised or the different stand types should be assessed with different parameters. The segmentation procedure is originally developed for aerial photos and adapted afterwards for laser scanner data. Therefore, the segmentation procedure may not fully exploit the capability of 3-dimensional tree height models.

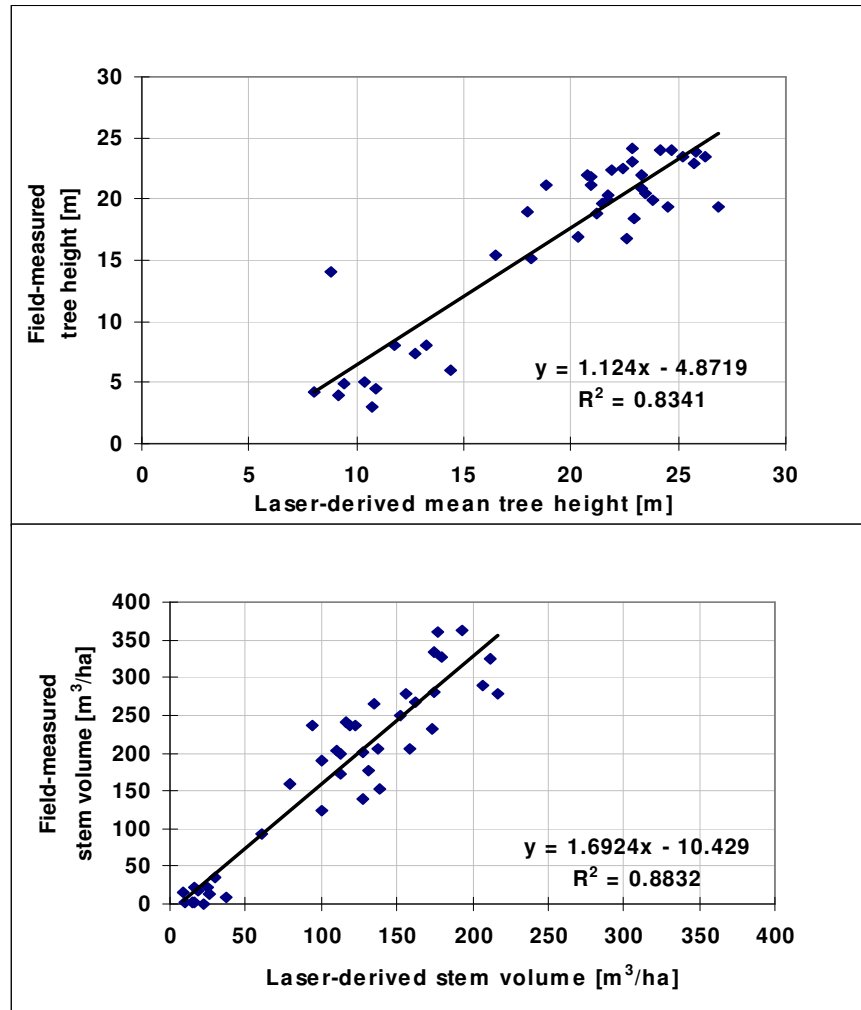


Figure 6. The scatterplots between the laser-derived and field-measured estimates.

The high coefficient of determination ( $R^2=0.89$ ) obtained for the basal area suggests a rather good capability to find individual tree crowns by the segmentation procedure. The obtained accuracy 1.9 m<sup>2</sup>/ha (9.6 %) suggests a better performance than using conventional forest inventory. However, a large systematic underestimation is due to improper calibration (Equation (3), segmentation parameters) and due to the fact the only the trees in the dominant layer were found. The regression-based model converting crown diameter to stem diameter was formed by using only 25 individual tree measurements. The use of tree height in Equation (3) improved the coefficient of determination from 0.72 to 0.89. The results are especially promising since the basal area is the most difficult parameter to assess using laser scanner.

The estimates for the stem volume summarize the above-discussed results, since the parameters affecting the stem volume are the basal area and mean height. The results, however, suggest a promising capability for operational forest inventories giving more accurate estimates ( $R^2=0.98$ , standard error 16.5 m<sup>3</sup>/ha, 9.5 %) than using conventional forest inventory. The correction of the overestimation in the mean height and underestimation in the basal area measurements resulted in an underestimation of stem volume. That underestimation after correction of parameters in Equation (3) should be corrected by introducing the diameter distributions of typical forests within the target area. Smaller trees not visible should be corrected by adding corresponding tree information from these distributions.

Comparing the results with Hyypä and Hyypä (2000a) in which statistical predictors and linear regression were applied to derive mean height and the stem volume, it can be concluded that single-tree-based segmentation provides slightly improved results compared to statistical methods. For the stem volume, Hyypä and Hyypä (2000a) obtained standard error of 23.6 m<sup>3</sup>/ha. Since the single-tree-based method is more physically oriented and it requires much less calibration than regression-based methods, it is anticipated that single-tree-based methods are more beneficial for operational activities.

The proposed method is useful especially in sparse mature stands. Difficulties were found especially in dense forests, where single trees were not easily identified. In dense parts the crown area is usually underestimated, because trees grow partly interlocked, and in such cases the segmented areas should be corrected, for example, with the calibration model. It is also obvious that only crowns in the top layer can be detected and the smaller trees underneath remain invisible.

## 7. CONCLUSION

The paper described a novel method to generate tree height models, principle how individual trees can be assessed using 3-dimensional tree height models, and the estimation results. The results are the first extensive results obtained with high-pulse-rate laser scanners for standwise forest inventory utilizing the capability to detect individual trees and determine their characteristics (height, location, crown dimensions) and to fully exploit the single treewise results to larger areas, such as standwise forest inventory.

It was shown that tree heights of individual trees in the dominating storey can be obtained with less than 1 m standard error. In addition, the following standard errors were obtained for mean height, basal area and stem volume at stand level: 2.3 m (13.6 %), 1.9 m<sup>2</sup>/ha (9.6 %), and 16.5 m<sup>3</sup>/ha (9.5 %), respectively. The obtained accuracy satisfied the requirements of operational standwise forest inventory.

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