A Segmentation-Based Method to Retrieve Stem Volume Estimates from 3-D Tree Height Models Produced by Laser Scanners

Juha Hyyppä, Olavi Kelle, Mikko Lehikoinen, and Mikko Inkinen

***Abstract*—In the boreal forest zone and in many forest areas, there exist gaps between the forest crowns. For example, in Finland, more than 30% of the first pulse data of laser scanning 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^2. This allows detailed investigation of forest areas and the creation of a three-dimensional (3-D) tree height model. Tree height model can be calculated from the digital terrain and crown models both obtained with the laser scanner data. By analyzing the 3-D 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.**

This paper demonstrates for the first time that it is possible to accurately estimate standwise forest attributes, especially stem volume (biomass), using high-pulse-rate laser scanners to provide data, from which individual trees can be detected and characteristics of trees such as height, location, and crown dimensions can be determined. That information can be applied to provide estimates for larger areas (stands). Using the new method, the following standard errors were demonstrated for mean height, basal area and stem volume: 1.8 m (9.9%), 2.0 m^2/ha (10.2%), and 18.5 m^3/ha (10.5%), respectively. The precision obtained is better than that in conventional standwise forest inventories.

***Index Terms*—Forest inventory, laser, remote sensing.**

I. Introduction

THE PROCESS of traditional field-based forest inventory is expensive and time-consuming, but it has been the only method for getting accurate data for small-area forest inventory. Satellite images, e.g., Landsat and Spot images, have been used in multisource forest inventory giving rather reliable estimates for forest attributes in areas of larger than approximately 100 ha. Stand attributes at stand level (stands are considered as homogeneous forest units, typically 1–3 ha in size) have been interpreted visually from high-resolution aerial images, and proven to be time consuming and quite sensitive to systematic error [1]. The rapid development of computer-related techniques has enabled the introduction of the powerful process of semi-automated forest inventory based on delineation of single tree crowns. Several authors have achieved promising results [2]–[5]. 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. Hugershoff [6] presented the concept of producing stand profiles (cross-sections of forest canopy) as early as 1939. He introduced the use of stand profiles for preparing stand aerial volume tables. It was not until in the 1980s when automatic profiles were taken, first with a laser and then with a radar. Nelson *et al.* [7], [8] 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 [9] 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 [7]–[11]. These earlier studies were based on vertical canopy probing, and the applied instruments were not capable of measuring anything but the forest under the flight line. Despite this, better performance of the nonscanning profiling radar over aerial photographs and imaging spectrometer demonstrated by Hyyppä *et al.* [11] suggests a good potential of profiling sensors for forest inventory.

Recently, the application of laser scanners to forestry has been demonstrated [12] and a European-wide project (HIGH-SCAN) to demonstrate its usefulness for forest inventory at the stand level has been launched [13]. The laser scanners are capable of recording a digital 3-D 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 was found that the disadvantages of lasers for forest inventory include limited penetration and ground detection capability through vegetation and reduced probability to

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detect treetops (since the laser beam is typically very narrow) [7], [8]. 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^2. This allows a detailed investigation of forest areas and the creation of 3-D tree height models. 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 analyzing the 3-D 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 physical dimensions from the trees and use that information to calculate the needed stand attributes.

This paper will demonstrate for the first time that high-pulse-rate laser scanners are capable to detect single trees in boreal forest zone, and automatic segmentation approach can be applied to retrieve important forest characteristics. The paper will concentrate on how the 3-D tree height model can be obtained, how the individual tree crowns can be delineated, and how the stand attributes can be calculated from the single tree data. The quality of the results will be tested by statistical analysis.

The work of the study was divided into the following tasks:

1) acquisition of laser data and field inventory data;
2) development and calculation of 3-D tree height model using the laser data;
3) automatic delineation of individual tree crowns using the tree height model;
4) derivation of standwise attributes from the individual tree information obtained by laser scanner;
5) verification of the developed method for standwise forest inventory.

II. Data Acquisition

A. Test Site

The boreal test site, Kalkkinen, is located in southern Finland, 130 km north of Helsinki. The 2 km $\times$ 0.5 km test site (100 ha) 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 1.3 ha.

B. Field Inventory

Conventional standwise forest inventory was carried out from August to October 1996, using sample plots and personal experience. From these data, mean tree height [m], basal area [m^2/ha], and stem volume per ha [m^3/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 photographs were taking in parallel with the field inventory and laser campaign. Changes were monitored visually and changed stands were rejected from further analysis. By the use of standard growth models, the stand attributes from 1996 to 1998 were updated. The descriptive statistics of the stand attributes information used for analysis are shown in Table I.

TABLE I
DESCRIPTIVE STATISTICS OF THE FIELD INVENTORY DATA

Character	*Mean Height*	*Basal Area*	*Volume*
Mean Value	18.1 m	19.6 m^2/ha	176.2 m^3/ha
Standard Deviation	5.6 m	8.72 m^2/ha	97.2 m^3/ha
Minimum Value	4.5 m	0.53 m^2/ha	2.2 m^3/ha
Maxim Value	24 m	32 m^2/ha	334.8 m^3/ha

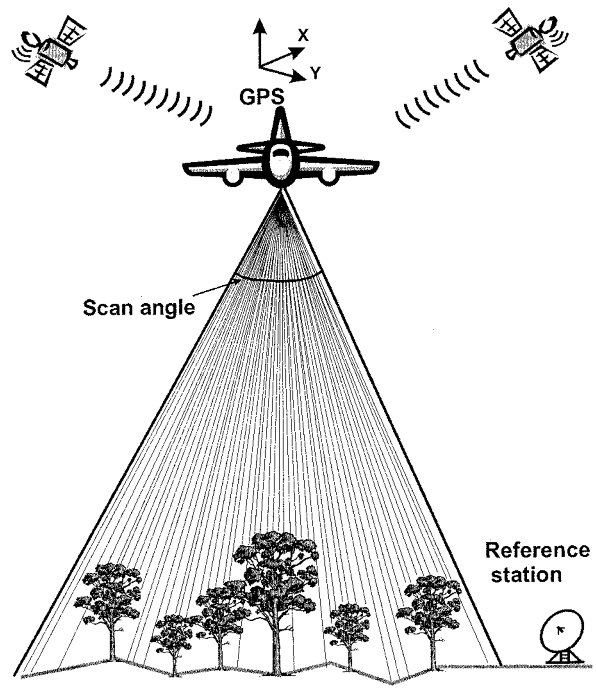

Fig. 1. Measurement principle of laser scanning over forest areas.

C. 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 coordinates of the reflecting object. The scanning mechanism sweeps the laser beam across the flight line, providing coverage across the flight track. The detailed measurement principle of laser scanning over forested areas is depicted in Fig. 1.

Using 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 [14] 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 digital elevation model (DEM) occur more frequently. The profiling capability of previous profiling sensors is 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. The first pulse should record more of the treetops and last pulse will detect more of the ground level hits. The 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 II.

The laser scanner campaign was carried out on September 2–3, 1998. The 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-km- × 0.5-km test site was intensively flown from the altitude of 400 m, resulting in measurement density equivalent of about ten measurements per m^2. Due to overlapping with parallel flight swaths, the measurement intensity exceeded in many places 20 pulses per m^2. The survey altitude was half of that in normal use 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 used.

TABLE II
TOPOSYS-1 LASER SCANNER PERFORMANCE PARAMETERS

Parameter	**Performance(s)**
Sensor	Pulse-modulated, TopoSys-1
Laser pulse frequency	83 000 Hz
Scan frequency	630 Hz
Field of View	± 7.1 degrees
Measurement density	8…10 per m^2 at 400 m
The number of shots per scan	128 parallel shots (one of which is the reference)
Swath width at 400 m	100 m
Position accuracy	X,Y < 1.0 m
Elevation accuracy (WGS84)	Z < 0.15 m
Laser classification	Class 1 by EN 60825 (eye-safe)

III. CALCULATION OF TREE HEIGHT MAP

The data was calibrated with the calibration flight from cross-tracks over the Kalkkinen area. The systematic errors occurred in the transformation were corrected using ground control points of summer cottages, road junctions, and the base map.

The 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 a 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 a digital crown model (DCM). The difference between the DCM and DTM models is called in this study a digital tree height model (DTHM), a 3-D 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 coordinates is transformed into a grid. When individual tree crowns are assessed, a requested resolution is about 50 cm requiring about ten laser-based samples per m^2. 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) or there are diverging points, 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 × 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 three to four iteration steps are needed at maxim.

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. 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 method together with the Delaunay triangulation.

Fig. 2 shows a perspective view of the obtained digital tree height model in a small sample area.

IV. SEGMENTATION PROCESS

The aim of the segmentation process was to delineate individual tree crowns. Typically, trees can be found by looking at the local maxims in the laser-derived tree height model. The complete segmentation applied consisted basically of the following stages:

1) prefiltering;
2) seed point extraction;
3) seeded region growing.

The tree height model derived from the laser scanner was prefiltered using the low-pass (diffusion) filtering. The optimal diffusion scale value corresponds to the situation where all local

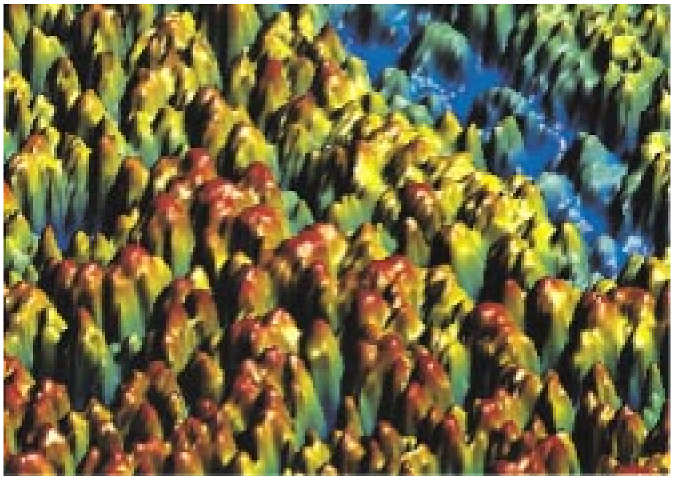

Fig. 2. Perspective view of laser-derived tree height model. The pseudo-colors are also used to indicate height, red representing tallest trees and blue the lowest.

intensity fluctuations due to noise are suppressed and all tree branches are merged to a region having a single maxim. Adjacent tree crowns should not be merged yet. A simple convolution with a 3×3 filter

$$[1\ 2\ 1 \quad 2\ 4\ 2 \quad 1\ 2\ 1]/16$$

was used.

The significant local maxims having values greater than the seed threshold $\boldsymbol{thSeed}$ were selected as seed points Fig. 3.

A local maxim was a point (i, j), where diffused image has values greater than any of its eight neighbors

$$(i-1, j-1), (i-1, j), (i-1, j+1), (i, j+1), (i, j+1), (i+1, j-1), (i+1, j), (i+1, j+1).$$

The delineation of individual tree crowns was modeled by means of an image labeling process. At the beginning, the only pixels with known label were the seed points, each of them having a unique label: the index of the seed point. Other pixel labels were uncommitted (marked as unknown), and the segmentation was an iterative process of committing the labels, i.e., marking pixels after the corresponding seed point. The areas of the same label correspond in our model to individual tree crowns.

The details of the segmentation algorithm were as follows.

Algorithm 3.1

1. Select seed points $S1 \ldots Sm$.
2. Initialize the Active Boundary Queue $\boldsymbol{Q}$, containing all seed points. Initialize label map $\boldsymbol{L_{ij}}=\boldsymbol{k}$, if pixel $(\boldsymbol{i}, \boldsymbol{j})$ is a seed point with index $\boldsymbol{k}$. Otherwise set $\boldsymbol{L_{ij}}=\boldsymbol{0}$.
3. Decrease the threshold: $\boldsymbol{th}=\boldsymbol{th}-\boldsymbol{thStep}$. If the minimum threshold $\boldsymbol{th}\mathbf{Min}$ have reached, then stop.
4. Take a next pixel $(\boldsymbol{i}, \boldsymbol{j})$ from queue $\boldsymbol{Q}$. If this is the end of the queue, go to **Step 3**.

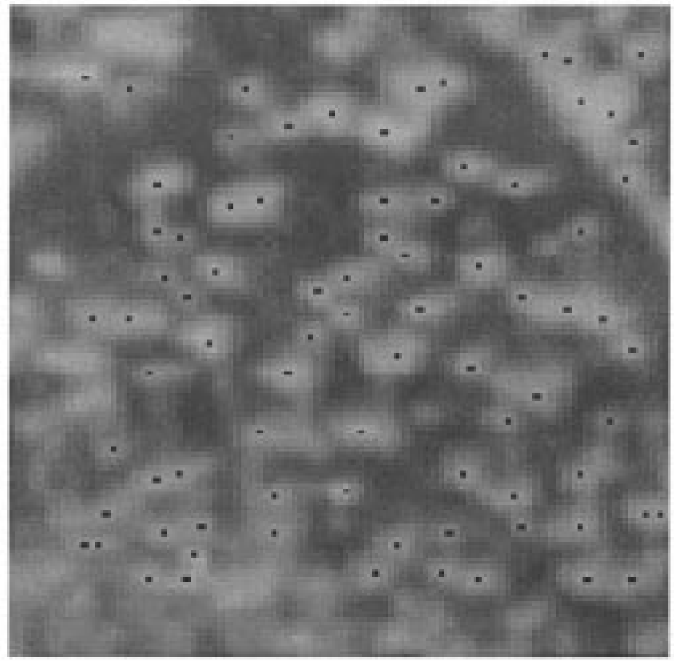

Fig. 3. Seed points (local maxims) calculated form prefiltered digital image.

5. Select the neighbor pixel $(\boldsymbol{i}', \boldsymbol{j}')$:from the set $\{(\boldsymbol{i}-\mathbf{1}, \boldsymbol{j}), (\boldsymbol{i}, \boldsymbol{j}-\mathbf{1}), (\boldsymbol{i}, \boldsymbol{j}+\mathbf{1}), (\boldsymbol{i}+\mathbf{1}, \boldsymbol{j})\}$. If there are no more neighbors left, go to **Step 8**.
6. If $(\boldsymbol{I_{i', j'}} > \boldsymbol{th})$ and **(dist** $((\boldsymbol{i}', \boldsymbol{j}')$,**GravityCenter** $(\mathrm{k})) < \max_{(\boldsymbol{i}, \boldsymbol{j})}$ **dist** $(\{(\boldsymbol{i}, \boldsymbol{j}) : \boldsymbol{L_{ij,}}_{=\boldsymbol{k}}$, **GravityCenter** $(\boldsymbol{k})))$, add pixel $(\boldsymbol{i}', \boldsymbol{j}')$ to the queue $\boldsymbol{Q}$ and mark the label $\boldsymbol{L_{i', j'}}=\boldsymbol{L_{ij}}$. Here **GravityCenter** $(\boldsymbol{k})$ is the gravity center of all pixels that are committed label $\boldsymbol{k}$ at current iteration step. As tree crowns are typically circular, the too elongated region is typically not an individual tree crown. To avoid such a phenomena, the last condition was introduced.
7. Go to **Step 5**.
8. If the pixel $(\boldsymbol{i}, \boldsymbol{j})$ has no more uncommitted neighbors, remove the pixel $(\boldsymbol{i}, \boldsymbol{j})$ from the Active Boundary Queue $\boldsymbol{Q}$.
9. Go to **Step 4**.

The segmentation process itself is a semi-automated approach in which the user controls the parameters $(\boldsymbol{mScale}$, $\boldsymbol{thSeed}$, $\boldsymbol{th}\mathbf{Min}$, $\boldsymbol{thStep})$ and sets them for each individual forest stands. The parameters values depend on the quality of the image (e.g., image brightness, resolution and texture features) and they were found by trial and error.

Scale parameter $\boldsymbol{mScale}$ controls the number of convolution filtering iterations. Without any filtering, the amount of tree crowns is typically too high. Too much filtering causes oversize for the tree crowns. Too high or low $\boldsymbol{thSeed}$ causes failure to recognize the correct number of individual trees. This parameter may easily be controlled visually during the process. The wrong setting of $\boldsymbol{th}\mathbf{Min}$ causes errors in estimated area of individual tree crowns. In order to control the shape of segmented individual tree crowns, parameter $\boldsymbol{thStep}$ was introduced. Higher values of $\boldsymbol{thStep}$ make the algorithm faster, but it may distort the shape of trees.

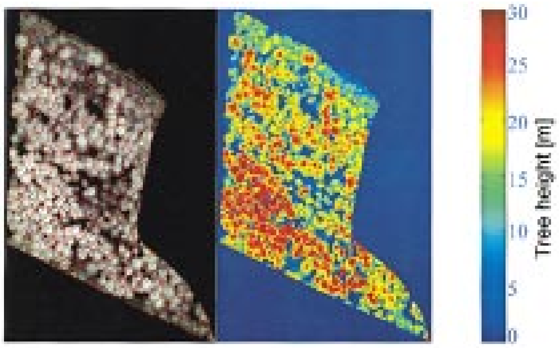

Fig. 4. Original laser-based tree height model and corresponding results: crown segments and localization of treetops. Pseudo-colors are used to indicate tree height from red (tallest) to blue (lowest).

Fig. 4 depicts an example of the segmentation results for derived tree height model.

V. 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 crown areas of each single tree. From that information, all other stand characteristics are derived.

A. Individual Tree Parameters

The location of the tree crown was determined by the center or maximum location of each tree segment.

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

$$h = \max(h_i) \tag{1}$$

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:

$$L = \sqrt{\frac{4A}{\pi}}. \tag{2}$$

In the boreal forest zone, there exists a high correlation between the crown diameters and the breast height diameter d for tree species such as *Pinus sylvestris, Picea abies, Betula pubescens,* and *Betula pendula* when stratification into height classes is made [15], [16]. 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 a laser scanner, the following regression formula was derived:

$$d = \alpha L + \beta h + \gamma \tag{3}$$

where coefficients α, β, and γ can be calibrated using local field inventory data.

The basal area of the single tree (m^2/ha) g is

$$g = \frac{\pi}{4} d^2. \tag{4}$$

The stem volume (m^3/ha) of single tree is obtained by Laasasenaho's formulas [17], in which volume is estimated using stem diameter d and height of the tree h.

B. Standwise Attributes

Standwise estimates were defined by calculating single tree attributes within the specified area. Standwise volume V [m^3/ha], basal area BA [m^2/ha], and mean height H [m] were expressed as

$$V = \sum_i v_i S \tag{5}$$

$$BA = \sum_i g_i S \tag{6}$$

$$H = \frac{\sum_i h_i g_i}{\sum_i g_i}. \tag{7}$$

S is constant converting the values to value per hectare. The mean height was calculated as Lorey's mean height (weighted by the basal area of each tree).

VI. Evaluation Method

The aforementioned methods (Sections III–V) were implemented. 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 the same parameters were applied for all stands selected. Therefore, the method was applied in an automatic manner. For the demonstration test, 15 stands were selected.

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

$$\mathrm{MSE} = \sum_{i=1}^{n} (e_{1i} - e_{2i})^2/(n-1) \tag{8}$$

where

e_{1i} result obtained with the described laser-based method for stand i;

e_{2i} corresponding field measured value;

n number of stands.

Since accuracy of the conventional forest inventory affects on the evaluation, the accuracy of conventional inventory was assessed [11] and the errors due to inaccuracy of the field inventory were removed from the MSEs. The systematic error of conventional field inventory was obtained by assuming that there is no bias in intensive field checking which were carried out to determine the accuracy of field inventory. The corrected root MSE (RMSE) was divided into two parts: systematic error x and standard error of the estimate s as derived from

$$x = \sum_{i=1}^{n} (e_{1i} - e_{2i})/(n-1) \tag{9}$$

$$s = \sqrt{\mathrm{RMSE}^2 - x^2}. \tag{10}$$

VII. Results and Discussion

Table III summarizes the results obtained for 15 stands. The mean tree height was obtained with 1.8 m standard error (conventional field inventory 1.7 m). The overestimation can be explained by the fact that a laser scanner is able to detect only the trees that can be seen above (neglecting the small trees). Since the height of each tree in dominant storey can be assessed with 1-m accuracy [18], the standard error 1.8 m is most likely due to errors in field inventory (since the tree height is the most difficult attribute to be measured accurately in the forests by human measurements) that were not taking properly into account when calculating the corrected mean squared error and errors due to nonoptimal selection of segmentation parameters.

The obtained standard error for the basal area suggests a rather good capability to find individual tree crowns by the segmentation procedure. The obtained accuracy suggests a better performance than using conventional forest inventory. However, a large systematic overestimation is due to the undersegmentation. The applied parameters were either nonoptimal or the segmentation-based algorithm should be redesigned to overcome this problem. Especially small stands were overestimated, but this is mainly due to that fact that the same parameters in segmentation procedure were applied to all stands. Since the segmentation procedure is originally developed for aerial photos and adapted for laser-based tree height models, the segmentation procedure may not fully exploit the capability of 3-D tree height models. A better reason for overestimation was that no teaching material was applied. The regression-based model converting crown diameter to stem diameter was formed by using individual tree measurements in Eastern Finland. In the Kalkkinen test site, trees are much thinner than in Eastern Finland as compared to the trees of the same height. The regression models should be recalculated or at least calibrated for different geographical areas. Overestimation will drop dramatically by correcting these two error sources.

The estimates for the stem volume summarize the previously discussed results, since the parameters affecting the stem volume are the basal area and mean height. The results, however, suggest a huge capability for operational forest inventories giving more accurate results than using conventional forest inventory, which is 15–20%. The correction of the overestimation in height and basal area measurements should actually result in an underestimation of stem volume since not all of the trees are visible in laser image, and therefore the proposed method should actually provide underestimation for stem volume. That underestimation 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.

The proposed method is useful especially in mature coniferous stands. Difficulties are expected especially in dense parts (young stands) or in groups of deciduous trees, where single trees cannot be 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. The advantages of the laser data are that the tree height can be determined from the image, which helps in correcting false segmentation. In the future, a probability check for each crown segment size will be applied using the true height.

TABLE III
Summary of the Test Results

Data Source/Error	***Mean height***	***Basal Area***	***Volume***
Field inventory/Standard error	1.7 m	3.4 m^2/ha	35.8 m^3/ha
Field Inventory/Systematic error	+0.57 m	0.0 m^2/ha	+19.3 m^3/ha
Laser scanner/Standard error	1.8 m	2.0 m^2/ha	18.5 m^3/ha
Laser scanner/Standard error-%	9.9 %	10.2 %	10.5 %
Laser scanner/Systematic error	+ 0.9 m	+ 3.9 m^2/ha	+ 48.3 m^3/ha

The obtained precision implies that the parameters of segmentation algorithm can be easily determined, but the problem of systematic error must be corrected, e.g., by field data. Similar algorithms are applied using aerial photos, but in such applications, the parameters are fixed for each stand. In our approach, similar parameters were used in all stands, whether young or mature.

VIII. Conclusion

High-pulse-rate laser scanners are able to provide information at tree level and able to provide accurate 3-D tree height maps to be used for forest inventories at stand level, which is demonstrated in this paper for the first time. By using the tree height and crown boundary information obtained with the laser scanner for each individual tree, the stem volume and basal area for each tree were calculated and the standwise estimates for stem volume per ha, basal area per ha, and mean height were derived.

Using the new method, the following standard errors were demonstrated for mean height, basal area, and stem volume: 1.8 m (9.9%), 2.0 m^2/ha (10.2%), and 18.5 m^3/ha (10.5%), respectively. The precision obtained is better than that in conventional standwise forest inventories.

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