AUTOMATIC DERIVATION OF FEATURES RELATED TO FOREST STAND ATTRIBUTES USING LASER SCANNER

Juha HYYPPÄ[*], Hannu HYYPPÄ[**], Georg RUPPERT[***]
[*]Finnish Geodetic Institute, Finland
Department of Photogrammetry and Remote Sensing
Juha.Hyyppa@fgi.fi
[**]Helsinki University of Technology, Finland
Department of Electrical and Communications Engineering
Hannu.Hyyppa@hut.fi
[***]Joanneum Research, Austria
Institute for Digital Image Processing
Georg.Ruppert@joanneum.ac.at

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ABSTRACT

High-pulse-rate laser scanners are capable to detect single trees in boreal forest zone, since significant amount of laser pulses reflect directly from the ground without any interaction with the canopy. This allows detailed investigation of forest areas and the creation of a 3-dimensional tree height model. By extracting the height, location and crown dimension of the trees from the 3-dimensional tree height model obtained from laser scanner data, important tree attributes, such as stem volume, basal area, and age, can be estimated for single trees. By knowing the characteristics of single trees, forest characteristics for sample plots, stands and larger areas, such as stem volume per hectare [m^3/ha], basal area per hectare [m^2/ha], mean height, dominant height, mean age, number of stems [pc/ha] and development class, can be calculated. The automatic extraction of crown dimensions from 3-dimensional tree height models is based on segmentation. This paper describes the general method and gives a first indication of the performance of the developed method. 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^2/ha (9.6 %), and 16.5 m^3/ha (9.5 %), respectively. The accuracy was better than the accuracy of conventional standwise field inventory.

1 INTRODUCTION

One of the most potential applications using high-pulse-rate laser scanners is the forest inventory at the stand level. Forest stand is the smallest description unit of forests and it represents a homogeneous forest area with respect to forest resources and treatments needed. The size of the forest stand varies, normally, between 0.5 and 5 hectares. Presently, forest inventory data is collected primarily by means of field surveys, which is both expensive and time-consuming. Important forest attributes, including stem volume per hectare, are then assessed to these stands by measuring sample plots and individual trees, and by using personal experience. At this level of planning, the accuracy requirements on forest data are very high, typically a 15 % error is tolerated (standard error divided by the mean). Typical costs per hectare range between 15 and 20 USD/Euro of which about 50-60 % is used for data acquisition and recording - tasks that can be substituted by remote sensing.

In order to reduce the costs of forest management planning, remote sensing techniques have be studied intensively for the last decades. The national forest inventory of Finland was the first of its kind utilizing satellite data (Tomppo, 1991). Satellite remote sensing has been shown to be an appropriate tool to assess and monitor large-area forest attributes with reasonable accuracy levels. Presently, optical satellite images are widely applied in national forest inventories. Concerning the stand level, no single remote sensing data acquisition method has been shown to be accurate and cost-effective enough for operational forest inventory, despite intensive research utilizing both airborne and space-borne remote sensing techniques (Poso et al., 1984; Pussinen, 1992; Tokola and Heikkilä, 1997; Hyyppä et al., 2000a). Aerial photos have been widely accepted to assist in the process, but automatic derivation of stand parameters is constantly an aim of several research groups. Recently, promising results have been obtained by many authors using semi-automated forest inventory based on single tree crown delineation and aerial photos (Dralle and Rudemo, 1996; Gougeon, 1997; Brandtberg and Walter, 1998) or laser scanner (Hyyppä and Inkinen, 1999).

The airborne laser scanner offers huge opportunities for rapid estimation of tree height, timber volume, and forest biomass over extensive forest areas. Previously, laser systems applied for forest studies were profiling sensors capable of data collection merely along the flight track, such as in Nelson et al. (1984, 1988) or the pulse rate of the laser scanner hindered the capability to detect individual trees (Nässet, 1997). 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-dimensional tree height map. 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.

This paper discusses automatic assessment of forest attributes by means of laser scanning.

2 MATERIAL

2.1 Test Site

The boreal forest test site, Kalkkinen, is located in southern Finland, 130 km north of Helsinki. This rather typical boreal forest area was selected for the study in order to maximize the availability and adequacy of good field inventory data and remote sensing data. An intensive area of 100 hectares (2-km-by-0.5-km) was selected for the detailed study. The test site is dominated by minor hills, otherwise it is flat and situated 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

Standwise field data. Conventional stand-wise forest inventory was carried out on August-October 1996 using sample plots and personal experience. 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. In order to monitor the cutting activity and other changes occurring between autumns 1996 and 1998 (laser acquisition), aerial photograph was taking 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.

Character	Mean height	Basal area	Volume
Mean value	16.9 m	19.3 m^2/ha	174.7 m^3/ha
Standard deviation	7.0 m	10.5 m^2/ha	115.4 m^3/ha
Minimum value	3.0 m	0.3 m^2/ha	1.0 m^3/ha
Maximum value	24.2 m	34.3 m^2/ha	361.4 m^3/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 5th 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, 25 trees were used to derive the ratio between the crown area and stem diameter.

2.3 Laser Scanning Measurements

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. 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 DTM 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.

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 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, but only first pulse mode was used for the creation of the 3-dimensional height model of the forest.

3 PRE-PROCESSING OF LASER DATA

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.

3.1 DTM Generation

There exist several algorithms to produce the DTM, but a rather new approach (Pyysalo, 2000; Hyyppä et al., 2000c) is described here in brief.

The generation of DTM includes five phases (Pyysalo, 2000):

1. Calculation of the original reference surface
2. Classification of vegetation and removal of vegetation from the reference surface
3. Classification of the original cloud of points using the reference surface
4. Calculation of the DTM based on classified ground hits
5. Interpolation of missing points

Calculation of the original reference surface was done by transforming the cloud of x, y and z co-ordinates into a grid and by recording the minimum terrain height z of all points corresponding to certain cell location. Classification of vegetation was performed using filtering. It was assumed that the ground surface is continuous and terrain elevations do not significantly change locally. A gradient of the matrix was calculated as a sum of differences of near-by pixels and as a sum of absolute values of differences of near-by pixels according to the formulas. The calculated gradient values were compared with a threshold value: if either of the gradient values was less than the threshold, the elevation corresponding to pixel was labelled as ground hit. Otherwise it was assumed as vegetation hit. The new elevations for the vegetation hits were calculated by Delaunay interpolation algorithm and by using of the terrain heights of near-by pixels. The process is iterative, typically 3 to 4 iterations are recommended. Classification of the original cloud of points was performed using the calculated reference surface. The terrain height of original points was compared against the calculated reference surface and the difference dz_n was calculated as follows

$$dz_n = z_n - z(j,i) \qquad (1)$$

where z_n is the terrain height of original points, and
z(j,i) is the terrain height of corresponding pixel in calculated reference surface.

Depending on the terrain type and slope, the difference dz_n value has to be specified. In Pyysalo (2000), it was found that the hits between the minimum and 60 cm above it formed an ideal cloud of point to be used for final DTM calculation. Mean and median values of classified ground hits were used for DTM calculation. The missing terrain heights was interpolated by using the near-by heights and Delaunay algorithm.

In Pyysalo (2000) and Hyyppä et al. (2000c), the accuracy of the DTM algorithm was verified to be 22 cm in boreal forest area. The terrain type and slope affected strongly the accuracy.

3.2 DTHM Generation

The maximum value of all the points within the resolution cell was calculated. It was found to represent rather well the tree tops. When there were holes (no data), the value for these points were obtained by interpolation and using the knowledge of nearby pixels. Diverging points in the digital crown model were detected by gradient method and thresholding. 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.

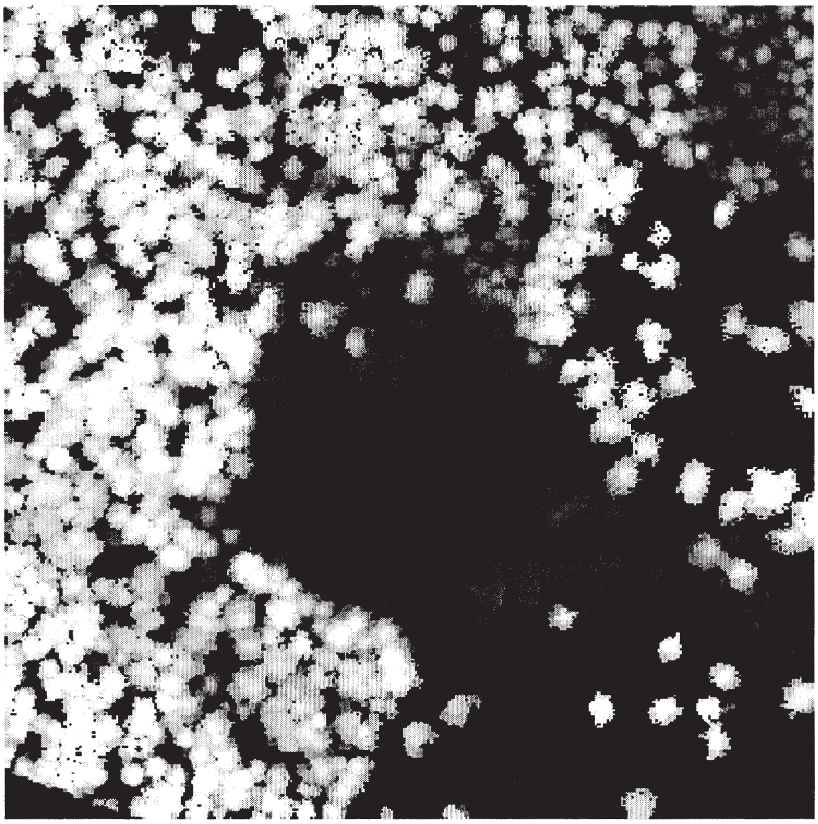

Figure 1.Obtained digital tree height model for a sample area. Individual tree crowns can be easily seen.

3.3 Segmentation

The segmentation of an image can be defined as its partition into different regions, each having certain properties (Soille, 1999). In the segmented image, the elementary picture elements are no longer the pixels but connected set of pixels.

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 (Hyyppä et al., 2000b).

The complete segmentation applied (Hyyppä et al. 2000c) comprises of the following stages: 1) the pre-filtering, 2) seed point extraction, 3) seeded region growing, and 4) oversegmentation/ undersegmentation correction.

3.4 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.

3.4.1. Treewise attributes

The location of the tree was determined by the location corresponding to maximum tree height of each tree segment. The height of the tree h was the maximum value of tree height model within that segment.

$$h=\max(h_i), \tag{2}$$

where h_i are individual tree heights of digital tree height model within the corresponding segment area. The crown diameter was calculated using the segmented crown area A information as follows

$$L=\sqrt{\frac{4A}{\pi}} \tag{3}$$

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 (1950) 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.

Therefore, the model relating stem diameter with crown diameter has to be calculated for each tree species that the system is capable to detect. Since the height correlates strongly with stem diameter and height can be assessed accurately with laser scanner, the following regression formula was derived

$$d=\alpha L+\beta h+\gamma \tag{4}$$

where coefficients α ,β and γ were calibrated using local field inventory data. However, in this demonstration an average model relating stem diameter and crown diameter was formed.

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

$$g=\frac{\pi}{4}d^2 \tag{5}$$

The stem volume (m^3/ha) of single tree were obtained by Laasasenaho's formulas (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).

$$\text{Pine}\quad v=0.036089\, d^{2.01395}\,(0.99676)^d\, h^{2.07025}\,(h-1.3)^{-1.07209} \tag{6}$$

$$\text{Spruce}\quad v=0.022927\, d^{1.91505}\,(0.99146)^d\, h^{2.82541}\,(h-1.3)^{-1.53547} \tag{7}$$

$$\text{Birch}\quad v=0.011197\, d^{2.10253}\,(0.986)^d\, h^{3.98519}\,(h-1.3)^{-2.65900} \tag{8}$$

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.

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

$$S = \frac{10000}{R}, \tag{9}$$

where R is the area (in square meters) specified by the stand boundaries. Standwise volume V [m^3/ha], basal area BA [m^2/ha] and mean height H [m] were expressed as

$$V = \sum_i v_i S \tag{10}$$

$$BA = \sum_i g_i S \tag{11}$$

$$H = \frac{\sum_i h_i w_i}{\sum_i g_i} \tag{12}$$

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

$$N = \max(i) S, \tag{13}$$

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

3.5 Evaluation Procedure

The above mentioned methods (Sections 3.1 to 3.4) 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 was cm. The use of several tree species within the same model deteriorated the performance. In near future, automatic tree species classification is included in the system to improve the total accuracy.

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.

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

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

where $Var(\delta_i)$ refers to variance of conventional field inventory error δ_i for stand i. The accuracy of field inventory measurement was verified in earlier study (Hyyppä et al., 2000a).

The RMSE was divided into two parts, systematic error x and standard error of the estimate s.

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)

$$R^2 = \frac{SSEA - s^2}{SSEA} \tag{15}$$

4 RESULTS AND DISCUSSION

Table 2 summarizes the results obtained for 41 stands. The estimated accuracy of field inventory is better than reported in Hyyppä et al.(2000a) since the stand size of the applied material is higher than that used by Hyyppä et al. (2000a). The effect of stand size was corrected according to results reported by Hyyppä and Hyyppä (2000).

Table 2. Summary of the accuracy estimation.

Data Source/Error	Mean height	Basal Area	Volume
Field inventory/Standard error	1.7 m	3.0 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	2.3 m	1.9 m^2/ha	16.5 m^3/ha
Laser scanner/Standard error-%	13.6 %	9.6 %	9.5 %
Laser scanner/Systematic error	+ 2.5 m	- 9.7 m^2/ha	- 65 m^3/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 behaviour (field inventory giving too low estimate). Since it has been found in this study and in previous study (Hyyppä et al., 1999) that 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.

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, Table 2. The obtained accuracy of 1.9 m^2/ha (9.6 %) suggests a better performance than by using conventional forest inventory. However, a large systematic underestimation is due to improper calibration (Equation (4), 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 (4) 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^3/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 (4) 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 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.

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REFERENCES

Brandtberg, T., and Walter, F., 1998. Automated delineation of individual tree crowns in high spatial resolution aerial images by multiple-scale analysis. Machine Vision and Applications, vol. 11, pp. 64-73.

Dralle, K., and Rudemo, M., 1996. Stem number estimation by kernel smoothing in aerial photos. Canadian Journal of Forest Research, 26, pp. 1228-1236.

Gougeon, F., 1997. Recognizing the Forest From the Trees: Individual Tree Crown Delineation, Classification and Regrouping for Inventory Purposes. In: Proceedings of Airborne Remote Sensing Conference and Exhibition, 7-10 July 1997 Copenhagen, Denmark, vol. 2, pp. 807-815.

Hyyppä, H., and Hyyppä, J., 2000, Effects of stand size on remote sensing-based forest inventory, manuscript.

Hyyppä, J., Hyyppä, H., Inkinen, M, Engdahl, M., Linko, S., and Zhu, Y-H., 2000a. Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. Forest Ecology and Management, 128, pp. 109-120.

Hyyppä, J., Hyyppä, H., and Samberg, A., 1999. Assessing Forest Stand Attributes by Laser Scanner. In: Laser Radar Technology and Applications IV, Proceedings of SPIE, 3707: 57-69.

Hyyppä, J., and Inkinen, M., 1999. Detecting and estimating attributes for single trees using laser scanner. The Photogrammetric Journal of Finland, 16, pp. 27-42.

Hyyppä, J., Kelle, O., Lehikoinen, M., Inkinen, M., 2000b. A segmentation-based method to retrieve stem volume estimates from 3-dimensional tree height models produced by laser scanner. manuscript.

Hyyppä, J., Pyysalo, U., Hyyppä, H., Haggrén, H., and Ruppert, G., 2000c. Accuracy of laser scanning for DTM generation in forested areas. Submitted for Laser Radar Technology and Applications V (AeroSense'2000).

Ilvessalo, Y., 1950. On the correlation between the crown diameter and the stem of trees. Publications of Finnish Forest Research Institute, vol. 38(2), 32 p.

Laasasenaho, J., 1982. Taper curve and volume functions for pine, spruce and birch. Commun. Inst. For. Fenn. 108.

Nelson, R., Krabill, W., and Maclean, G.A., 1984. Determining forest canopy characteristics using airborne laser data. Remote Sensing of Environment, 15, pp. 201-212.

Nelson, R., Krabill, W., and Tonelli, J., 1988. Estimating forest biomass and volume using airborne laser data. Remote Sensing of Environment, 24, pp. 247-267.

Nässet, E., 1997. Estimating timber volume of forest stands using airborne laser scanner data. Remote Sensing of Environment, vol. 61, pp. 246-253.

Poso, S., Häme, T., and Paananen, R., 1984. A method of estimating the stand characteristics of a forest compartment using satellite imagery. Silva Fennica, 18, pp. 261-292.

Pussinen, A., 1992. Ilmakuvat ja Landsat TM – satelliittikuva välialueiden kuvioittaisessa arvioinnissa. University of Joensuu, Faculty of Forestry, M.Sc. thesis, 48 p., (in Finnish).

Pyysalo, U., 2000. Metsäalueen korkeusmallin muodostaminen laserkeilaimella mitatuista kolmiulotteisesta pistejoukosta – Determination of elevation models in wooded areas with 3-dimensional point cloud measured with laser scanner. Thesis for the M.Sc. degree, Helsinki University of Technology, Department of Surveying, 68 p. (In Finnish).

Soille, P., 1999. Morphological image analysis, principles and applications. Springer.

Tokola, T., and Heikkilä, J., 1997. A priori site quality information in satellite image based forest inventory. Silva Fennica, 31, pp. 67-78.

Tomppo, E., 1991. Satellite image-based national forest inventory of Finland. In: International Archives of Photogrammetry and Remote Sensing, 28, pp. 419-424.

TopoSys, 1996. Digital Elevation Models, Services and Products, 10 p.