

## METHODS OF AIRBORNE LASER SCANNING FOR FOREST INFORMATION EXTRACTION

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### ABSTRACT

Extracting forest information from airborne laser scanner has become an own discipline within its 10 years of history. This paper summarizes new findings in extracting forest attributes from laser scanner data, the use of multitemporal data sets for forest growth estimation and in quality of digital terrain models of forested areas based on experiments conducted in boreal forest zone in Finland.

**Keywords:** Digital terrain model, individual tree crown, segmentation, height growth, laser scanner

### 1 INTRODUCTION

Airborne laser scanners (ALS) providing small footprint diameters (10 – 30 cm) allow accurate height determination of the forest canopy (e.g. Næsset 1997a, Magnussen and Boudewyn 1998, Magnussen et al, 1999, Means et al. 2000). The two main approaches in deriving forest information from laser scanner data have been the laser canopy height distribution based and the individual tree detection based approaches. In the laser canopy height distribution based method, percentiles of the distribution of laser canopy heights are used as predictors to estimate forest characteristics. For example, Næsset (2002), Lim et al. (2003) and Holmgren and Jonsson (2004) have shown that this approach produces highly reliable estimates of stand variables. If the number of laser pulses is increased e.g. to more than about three measurements per square meter, individual trees can be recognized (Brandtberg 1999, Hyyppä and Inkinen 1999, Persson et al. 2002, Popescu et al. 2002, Leckie et al. 2003). From individual trees, height of the tree, crown diameter and tree species are then derived using laser and possibly aerial image data.

Timber volume is usually the most interesting stand characteristic to be considered. When using the laser canopy height distribution based approach, laser-derived height quantiles are related to the stem volume (e.g. Næsset 1997b, 2002, 2004, St-Onge and Renaud 2001, Lim et al. 2003, Holmgren 2004). In the individual tree based method, the volume of the individual tree stems is calculated using existing formulas from height, crown diameter and species information. Presently also formulas relating diameter breast height and crown diameter have been further developed for laser scanning purposes (e.g. Kalliovirta and Tokola, forthcoming). A Scandinavian summary of laser scanning including obtained accuracies in forestry can be read from Næsset et al. (2004).

ALS provides 3D characterization of forest canopy. From the original point cloud, digital terrain model (DTM) and digital surface model (DSM) corresponding to treetops can be calculated. Points forming the DTM are calculated using so-called filtering algorithms. Most usable technique to obtain DSM relevant to treetops is to calculate the TIN of the highest reflections and interpolate missing points e.g. by Delaunay triangulation. The canopy height model (CHM) is then obtained by subtracting the DTM of the corresponding DSM. The crown DSM is typically calculated by means of the first pulse echo and DTM with the last pulse echo. In order to guarantee, that there are no systematic errors between first and last pulse data, calibration using flat, non-vegetated areas, such as roads, roofs, and sports grounds are typically performed.

This paper summarizes recent advances in extracting forest information from airborne laser scanner data based on the Finnish experiments.

## 2 TEST SITE AND MATERIAL

### 2.1 Test Site and Applied Laser Scanner Data

The test site was located in a state owned forest area of approximately 50 hectares located in Kalkkinen, southern Finland, 130 km north of Helsinki. The 2-km-by-0.5-km intensive study area situated about 110 m above sea level, with slopes ranging between 0 and 66° and with 87 % of forest cover dominated by species such as spruce, pine and birch, was collected with Toposys I in 1998 and 2000, and with Toposys II in 2003. In all campaigns, the pulse repetition frequency (83 kHz), maximum scan angle ( $\pm 7.1^\circ$ ), beam size (1 mrad) and wavelength of the system (wavelength of 1.5  $\mu\text{m}$ ) remained constant. The major difference between the Toposys I and II was the possibility to record first and last pulse simultaneously in the version II. Since the measurements were recorded at various times of the season, i.e. May 14<sup>th</sup> 2003 (leaf-off), June 14<sup>th</sup> 2000 (leaf-on, low development of undergrowth), and September 2<sup>nd</sup> 1998 (leaf-on, high undergrowth), it was possible to estimate the effect of leaves and undergrowth at boreal forest zone. That was performed using the high pulse density point cloud (8-10 pulses per  $\text{m}^2$ ) obtained from 400 m flight altitude in each acquisition. The effect of the flight altitude was studied using the flight altitudes of 400, 800 and 1500 m above ground level collected in 2003 providing nominal pulse densities of 8-10, 4-5 and 2-3 pulses per  $\text{m}^2$ .

### 2.2 Field Reference for Volume Estimation Improvement

During the summer of 2001, 33 systematically located rectangular sample plots were established on the test site. The basic size of a sample plot was 30 m by 30 m, but to get around 100 trees per plot, plot sizes of 25 m by 25 m and 30 m by 40 m were also used. Most of the sample plots included dense understorey and were dominated by Norway spruce, although, each sample plot included more than one tree species. All trees having a diameter at breast height (DBH) of more than 5 cm were mapped using a measuring tape, and tree species, DBH, tree height, and height to the living crown were registered. All individual trees were classified as belonging to either the dominant or the suppressed tree layer. On the average there were 414 dominant and 435 suppressed trees per hectare in the data. 78 pine trees in 10 plots were selected to be used in this study in Section 3.

### 2.3 Reference for Growth Analysis

For individual tree height growth analysis (Section 4), 82 pines were selected and height, location and shoot elongation of these trees were measured in August 2002 and November 2004 using a tachometer. In addition to measuring the height of the trees, five to seven consecutive shoots below the top of the tree were also measured.

### 2.4 Digital Terrain Model Reference

Theodolite Wild T2002 with Distometer Di2002 was used to measure tree locations and terrain height points. Typically, coordinates for tree location in north and east direction were measured to the centre of the trunk and the height was measured next to the tree, thus making it possible to use the tree coordinates for DTM determination as well. In most cases, DTMs were measured as a grid of ground points. Measured points were distributed evenly inside the plots with a distance from each other of about 2 m. Altogether 2119 points were recorded (Section 5).

Test plot 5: Mainly tall spruces together with few tall birches, on one corner a more dense area of smaller spruces, no bushes. The plot is located on a gentle slope and terrain is very smooth.

Test plot 9: Tall birches and smaller spruces below them, practically no undergrowth. Terrain is fairly smooth and gentle slope.

Test plot 10: Mainly full-grown trees of various species, some bushes in the undergrowth. A small cliff and fairly large height differences in the plot.

Test plot 14: Mainly full-grown trees of various species together with smaller and denser undergrowth of trees. Middle part of the plot flat, steep slopes of few meters on two sides.

Test plot 22: Mainly tall pines, main part of the plot on top of a small hill, steep slope on one side.

Test plot 26: Mainly full-grown trees of various species. Some dense bushes in the undergrowth. Terrain is fairly flat.

Test plot 30: Mainly saplings of various species, partly very dense growth. Test plot is located on a hillside, so large height differences within the plot.

Test plot 34: Mainly tall birches together with some tall pines and spruces. Plot is located on a gentle slope, otherwise flat terrain.

### 3 TECHNIQUES FOR VOLUME ESTIMATION

#### 3.1 Comparison of the Present Methods

As it was mentioned in the introduction, the two main approaches in deriving forest information from laser scanner data have been the statistical canopy height distribution based and the individual tree detection based approaches. There has not been careful comparison of these two techniques and the results obtained have been based on different type of reference data sets. Typically, distribution based techniques have been calibrated with a very large and accurate reference data and individual tree based approaches have not been properly calibrated at all. Thus, the obtainable results are not comparable. A short overview of the advantages and disadvantages of the techniques are given in Table 1.

Table 1. Comparison of distribution and individual tree based methods.

	Advantages	Disadvantages
<b>Distribution based methods</b>	<ul style="list-style-type: none"> <li>• Easy to integrate with present forest inventory practices due to common reference plots</li> <li>• Strong statistical background</li> <li>• Laser scanning data relatively inexpensive</li> </ul>	<ul style="list-style-type: none"> <li>• Requires large, accurate, representative, and expensive reference data</li> <li>• Without large number of reference data, the possibility to have high errors in operative inventory is high</li> </ul>
<b>Individual tree based methods</b>	<ul style="list-style-type: none"> <li>• Good physical correspondence (existing models) with volume estimation</li> <li>• Low amount of reference data needed for calibration</li> <li>• Allows precision forestry and increased information amount of the forests</li> </ul>	<ul style="list-style-type: none"> <li>• More expensive laser data</li> <li>• More complex system to be implemented</li> </ul>

In the following some other techniques are proposed and preliminary accuracy is either analyzed or discussed.

#### 4.1 Tree Cluster Based Inventory

The typical hypothesis for individual tree based laser inventory (Hyypä and Inkinen 1999) is that by measuring major individual tree characteristics, such as the height of the tree, tree species, and crown diameter, it is possible to derive other valuable tree characteristics, such as stem diameter, stem vol-

ume, and age for the same tree and to use these information to calculate standwise forest information (mean height, dominant height, stem volume, basal area, tree species proportions).

The accuracy obtained with the approach depends on the structure of the forest (number of tree layers, tree species, density), quality of images and density of laser point clouds and applied processing technique. It has been shown that trees can usually be recognized only in the dominant tree layer (Persson et al. 2002, Maltamo et al. 2004). Depending on the density of the forest and density of the point clouds, the discrimination of individual trees is a problem of varying complexity. In dense stands this leads to underestimation of the number of tree stems.

What about if the individual tree based technique is applied directly to tree clusters? A feasible algorithm could be

1. Moderate filtering to laser data in order to help in the finding of tree tops
2. Tree top finding of tree clusters
3. Rough segmentation using the top of the clusters
4. Analysis of large clusters

In the analysis part of the large clusters, there are several ways of performing the analysis. Analysis of tree species can be done either using digital aerial image or laser data (see e.g. Holmgren and Persson 2004) for each segment. Each segment is assumed to be homogeneous with respect to tree species. Based on the height of the tree and known tree species, an approximated crown diameter for one tree can be calculated. The relation between the size of the real segment and approximated crown area for one tree is used to estimate the number of trees. Alternatively, for smaller segments (1-4 trees in the segment), the existing volume formulas are used to directly estimate the volume corresponding to the trees in the segment.

In Hyypä et al. (2005), the latter approach was tested for volume estimation of individual tree groups. The results indicate that individual trees volumes can be obtained, roughly speaking, with random error about 30% and the volume related to small tree clusters or segments with random error of 37%. The  $R^2$  values were almost identical. In conventional forest inventory, the random error of the volume estimation of individual trees using the diameter as predictor is 17.2 % for Scots Pine (Laasasenaho, 1982). These models are still used to calculate the volume of the individual tree from manual diameter measurements. From that point of view, the results are good. The splitting of the segments did not improve the results in Hyypä et al. (2005), since the segments were already relatively small (1-3 trees) and most of the trees were optimally segmented.

In general the tree cluster technique is expected to work with lower density data (0.5-1 pulses per  $m^2$ ) and it should be superior to distribution based techniques since it utilizes the homogeneity of laser hits in a cluster. However, the techniques how to derive volume from larger segments (clusters) should be further investigated.

### 3.2 Inventory Using Old Look-Up Tables

An old way of getting stem volume per hectare is the use of look-up-tables based on basal area per hectare and mean height, such as Nyyssönen 1954. The mean height is obtainable from height distribution or by calculating the average value of tree heights corresponding to each tree segment. The basal area needs to be modeled either from the number of canopy hits (e.g. Nelson et al. 1988) or from sum of areas of segments with proper calibration with the height. By this technique, only the basal area needs to be properly calibrated with good reference data set and even heuristic and knowledge based rules can be defined to get good quality basal area statistics.

The technique should be more robust and not so dependant on high amount of good reference data as the direct distribution based method.

### 3.3 Extracting Height from Sparse Laser Data and Segments from Aerial Images

Individual tree crown based solutions have been first demonstrated with aerial images (e.g. Gougeon and Moore 1989, Gougeon 1997). In the case of aerial images and using individual tree based tech-

nique, the standard errors for volume estimation at stand level are usually considerably high being 35-60 % (Anttila and Lehtikoinen 2002, Huitu 2005, Korpela et al. 2005). However, sparse laser scanning data are becoming increasingly attractive due to state-wise laser scanning. It should be possible to improve the aerial image based estimates by giving the height for each crown (segment) using the sparse laser data.

In the test (Hyypä et al. 2005), CIR derived segments were first used to calculate volume of the trees, Figure 1. The low coefficient of determination obtained using only aerial image segment for volume estimation ( $R^2=0.13-0.14$ ) implies that at least in this test the obtained crown diameter did not correlate well with stem volume. The result was surprising, since proper segmentation for each tree was visually selected from seven possible choices and in typical ITC (individual tree crown) solution using aerial images, one stand is treated with same parameters in the segmentation. There was a large underestimation of stem volume, most probably due to the fact that the above-seen crown diameter was significantly smaller than that of the real one. Also, the trees are much taller and narrower (concerning crowns) in Kalkkinen than typical Finnish trees, in which Laasasenaho (1982) formulas are based on. It should be noticed that the test site has been difficult for remote sensing tests also previously, see Hyypä et al. (2000a). Anyhow, the results show that aerial image based individual tree crown approach does not work in all forest conditions.

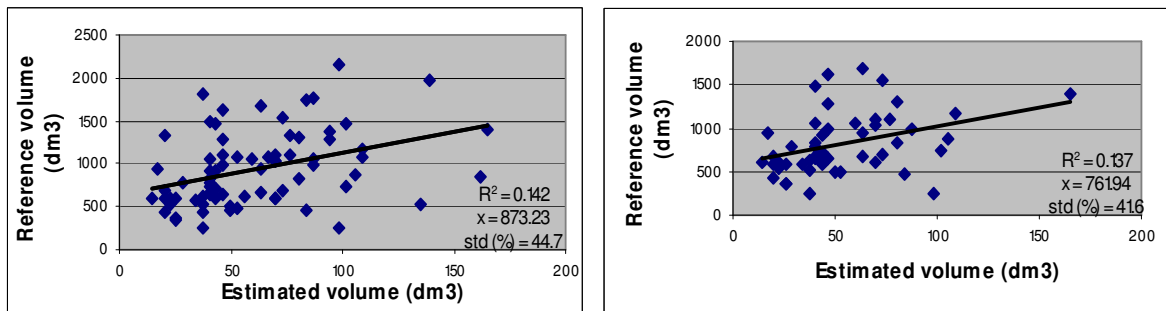
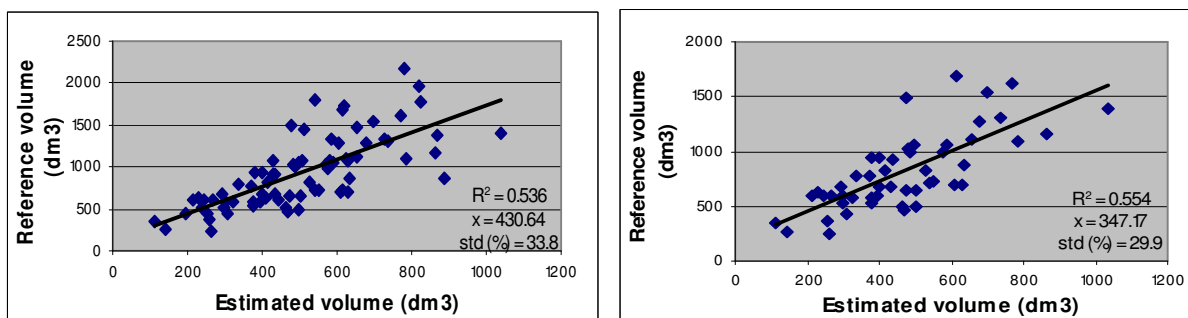


Figure 1. Scattergram between estimated and reference volume when estimation was done using only diameters of segments from CIR. The reference consists of all trees (left) and individual trees (right) within the segment. Left: mean volume  $934.4 \text{ dm}^3$  and std  $428.6 \text{ dm}^3$  for the reference; right: mean volume  $815.7 \text{ dm}^3$  and std  $349.3 \text{ dm}^3$  for the reference.

In the second phase (Hyypä et al. 2005), each CIR segment was given the height from the laser derived canopy height model. Stem volume was calculated using Laasasenaho (1982) formulas for pine using both the height and diameter at breast height of the stem. From Kalliovirta and Tokola (forthcoming), the relation between stem diameter and height and crown diameter was obtained.

There is a significant improvement in performance when tree height information was added into the aerial image based ITC solution, Figure 2. In addition to the improvement in  $R^2$  values, the underestimation was significantly reduced. The results obtained with segments including only one tree showed slightly better results (0.55-0.56, 29.9 % error in segment wise volume estimation) compared to all segments (0.54, 33.8 % error in segment wise volume estimation), but the difference was not significant.



*Figure 2 Scattergram between estimated and reference volume when estimation was done using diameters of segments from CIR and height from laser data. The reference consists of all trees (left) and only individual trees (right) in the segment. Left: mean volume 934.4 dm<sup>3</sup> and std 428.6 dm<sup>3</sup> for the reference; right: mean volume 815.7 dm<sup>3</sup> and std 349.3 dm<sup>3</sup> for the reference.*

### 3.4 Use of Old Inventory Data to Improve Distribution Based Techniques

The major disadvantage of the distribution based technique or the technique depicted in 3.2 is that they require large, accurate, representative, and expensive reference data. However, from the most Scandinavian forests, there exists 10-20 years old inventory data. With change detection techniques, e.g. image differencing with two BRDF (Bidirectional Reflectance Distribution Function) corrected aerial image, it is possible to find areas that have not changed. Such areas can be updated with existing growth models with reasonably accuracy. These updated forest attribute information can then be used to calibrate any of the laser-based techniques applied. Volumes for all areas can then be estimated with laser data, but the overall calibration is based on the unchanged stands where old inventory data is updated with growth models.

As an alternative to BRDF correction, channel difference or ratio images or NDVI-compatible images can be used to substitute original images.

### 3.5 Conclusions

Four new inventory techniques for laser scanner data were proposed. These four techniques should be either more cost-effective or more robust than the pure distribution based or individual tree based techniques. They all work with sparser point clouds than original individual tree based methodology and they are more robust than the original distribution based technology. However, more detailed studies are needed to define the accuracy of the methods.

## 4 CHANGE DETECTION FOR CANOPY HEIGHT GROWTH MEASUREMENTS

### 4.1 Background for Change Detection

Change detection in forests using multitemporal airborne laser scanner point clouds has been demonstrated recently (Yu et al. 2003, Hyypä et al. 2003, Yu et al. 2004, St-Onge and Vepakomma 2004, Gobakken and Næsset 2004). Yu et al. (2003, 2004) demonstrated the applicability of small footprint, high sampling density airborne laser scanners for estimating forest growth and the monitoring of harvested trees. Algorithms were developed for detecting harvested and fallen trees, and for measuring forest growth at plot and stand levels. An object-oriented tree-to-tree matching algorithm was presented to link the point clouds, one from each laser acquisition, of the same tree.

At the same time, the costs of laser scanning acquisition have decreased. Today, large areas (such as 500-10,000 km<sup>2</sup>) can be collected with reasonably good density (1 point per m<sup>2</sup>) at costs equivalent to 50-100 €/km<sup>2</sup>. The increase in PRF will lead to a situation where dense point clouds, such as 10 points per m<sup>2</sup>, can be collected for large forest areas at reasonable cost. This will allow commercially-oriented multi-temporal laser acquisitions in the near future.

The objective of this sub-study is to describe the potential for change detection using airborne laser scanners and the techniques and accuracies involved beyond those presented by Yu et al. (2004). In Yu et al. (2004), the accuracy of height growth was not examined in detail due to the lack of sufficient field data and some problems related to plotwise analysis. This paper not only describes individual tree height growth measurement, but also shows how it is derived using various techniques.

### 4.2 Methods

In this paper, three different change detection techniques are used to estimate growth

- Difference between DSMs (see Figure 3)
- Comparison between canopy profiles (i.e. cross-section of point clouds within a defined width), see Figure 4
- Analysis of difference between height histograms (see Figure 5)

The difference between DSMs is assumed to work in areas with wide crowns, but in coniferous forests with narrow crowns and tall trees (up to 35 m), the displacement between two acquisitions can be substantial. Height histograms can be applied to point clouds corresponding to individual trees or plots or stands, but the information contents of histograms is corrupted if thinning has occurred.

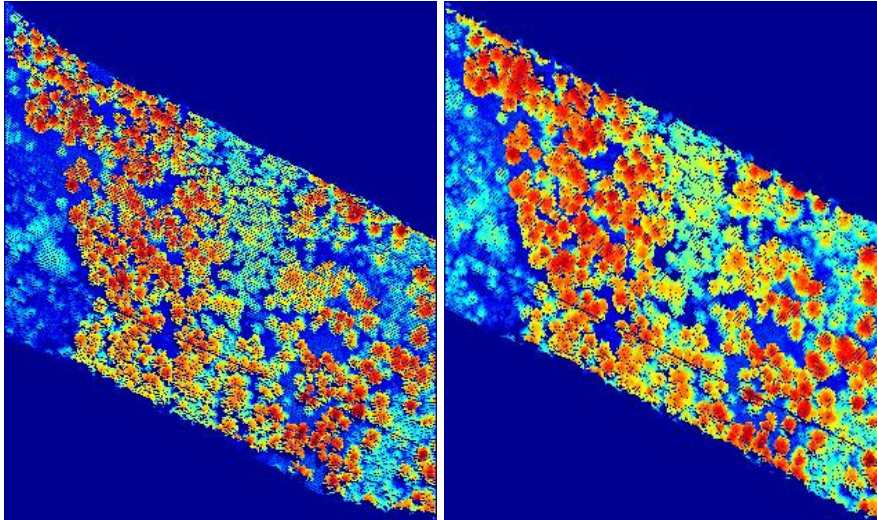


Figure 3. DSMs from 1998 (left) and 2003 (right) data. The line in the image is the location of the profiles in Figure 4.

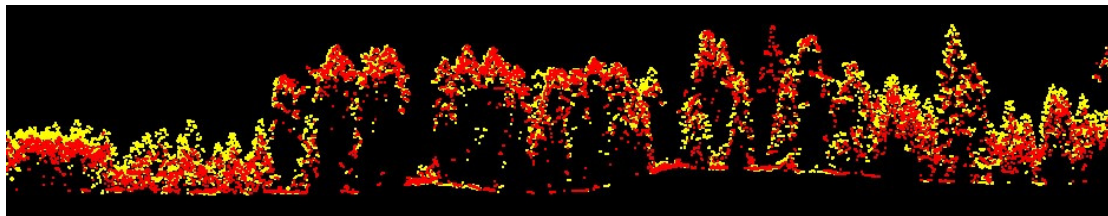


Figure 4. 3-m wide canopy profile for a 150-m long cross-section. Yellow: 2003, Red-1998.

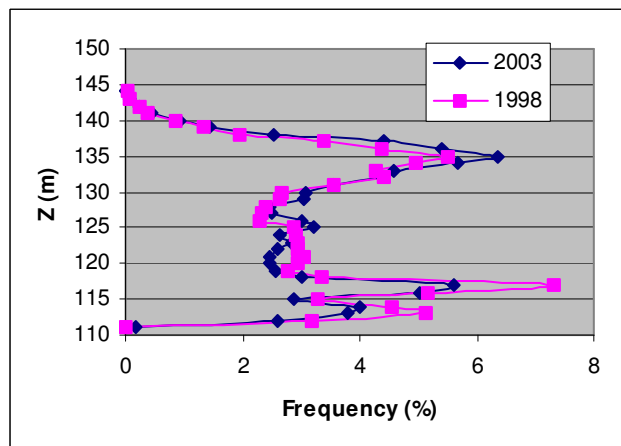


Figure 5. Histograms of corresponding profiles in Figure 4.



Eighty-two field-measured pine trees were used to demonstrate individual tree height growth. Since the location of the trees was known by reference measurements, treetop location on the laser acquisitions was searched in the close neighborhood of the field-measured location. The corresponding laser points falling within a cylinder around the found location of each trees were used to extract variables used for growth estimation. The radius of the cylinder, varied (between 0.76 to 3.58 m) according to the height of the tree. Three different types of variables were extracted from the point clouds using three techniques. First, the highest z value was taken among the points within the cylinder and the height growth was estimated as the difference between the highest z value in the 2003 and 1998 datasets (denoted by  $\text{MaxZ}_1 - \text{MaxZ}_2$ ). Secondly, the mean and median value of the difference between the DSMs (denoted by  $\text{Mean}(\text{DSM}_1 - \text{DSM}_2)$  and  $\text{Median}(\text{DSM}_1 - \text{DSM}_2)$ ) and the difference between mean and median value of the DSM between the 2003 and 1998 datasets (denoted by  $\text{Mean}(\text{DSM}_1) - \text{Mean}(\text{DSM}_2)$  and  $\text{Med}(\text{DSM}_1) - \text{Med}(\text{DSM}_2)$ ) were calculated. The DSMs were obtained by taking the highest point within each 50 cm grid. Thirdly, the height histograms of the point clouds for each tree were formed and the 85<sup>th</sup>, 90<sup>th</sup> and 95<sup>th</sup> percentiles were calculated. The height growth was assumed to be the difference between corresponding quantiles from the 2003 and 1998 datasets (denoted by  $\text{P85}_1 - \text{P85}_2$ ,  $\text{P90}_1 - \text{P90}_2$ ,  $\text{P95}_1 - \text{P95}_2$  respectively).

### 4.3 Results of Change Detection

Table 2 and Figure 6 show the results of individual tree height growth analyses. From all the techniques used, the difference between the treetops of each tree (in 1998 and 2003) resulted in the highest  $R^2$  value (0.68). The underestimation was 7 cm and the RMSE was 43 cm. By using the quantiles of the height histograms, the  $R^2$  values ranges between 0.51 and 0.6. The use of the mean or median of the difference between the DSMs or the difference between the mean/median of DSMs resulted in  $R^2$  values between 0.33 and 0.53. The results indicate that it is possible to measure the growth of an individual tree, which has already been reported earlier by Yu et al. (2005a).

Since the tree crown is not a continuous surface, the laser pulses penetrated through gaps in the crown and were reflected from a lower layer or the ground. This has caused problems in growth estimation using DSM differencing. The effect is more significant in the crown boundary than in the very top of the crown. Therefore, the same analyses were carried out using the data extracted for each tree with the cylinder radius reduced by half to avoid the boundary effects (Table 3). The results show that histogram-based growth estimation was improved and was almost as good as with the maximum point method. The methods based on DSM differencing were not significantly improved.

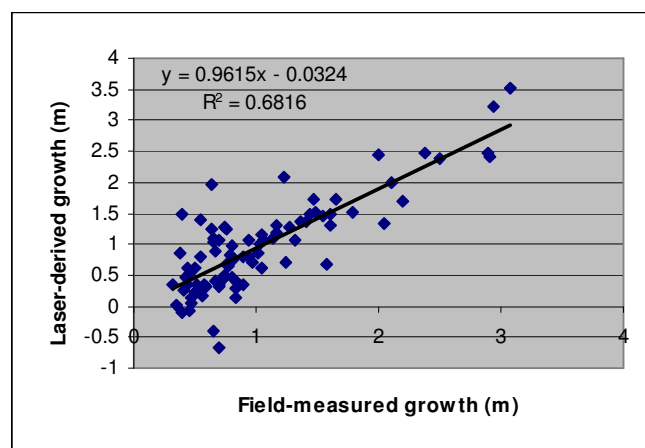


Figure 6. Scatterplot and line of regression of tree height growth estimation versus field-measured growth. Tree height growth was estimated from the differences of maximum Z values of point clouds between 2003 and 1998.

Table 2. Statistics of individual tree growths: full radius

Method	$R^2$	Bias (m)	Stdev (m)
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MaxZ <sub>1</sub> -MaxZ <sub>2</sub>	0.68	-0.07	0.43
P85 <sub>1</sub> -P85 <sub>2</sub>	0.51	0.16	0.51
P90 <sub>1</sub> -P90 <sub>2</sub>	0.55	0.10	0.48
P95 <sub>1</sub> -P90 <sub>2</sub>	0.60	0.01	0.48
Mean(DSM <sub>1</sub> -DSM <sub>2</sub> )	0.46	0.47	0.63
Median(DSM <sub>1</sub> -DSM <sub>2</sub> )	0.53	0.36	0.60
Mean(DSM <sub>1</sub> )-Mean(DSM <sub>2</sub> )	0.53	0.11	0.47
Med(DSM <sub>1</sub> )-Med(DSM <sub>2</sub> )	0.33	0.15	0.63

Table 3. Statistics of individual tree growths: half radius

Method	R <sup>2</sup>	Bias (m)	Stdev (m)
P85 <sub>1</sub> -P85 <sub>2</sub>	0.61	0.04	0.46
P90 <sub>1</sub> -P90 <sub>2</sub>	0.66	-0.04	0.43
P95 <sub>1</sub> -P90 <sub>2</sub>	0.66	-0.07	0.44
Mean(DSM <sub>1</sub> -DSM <sub>2</sub> )	0.49	0.30	0.58
Median(DSM <sub>1</sub> -DSM <sub>2</sub> )	0.53	0.24	0.53
Mean(DSM <sub>1</sub> )-Mean(DSM <sub>2</sub> )	0.44	0.24	0.57
Med(DSM <sub>1</sub> )-Med(DSM <sub>2</sub> )	0.38	0.32	0.62

#### 4.4 Conclusions

This sub-study demonstrated the use of various techniques to measure individual tree height growth. Differences between DSMs, height histograms and the highest laser hits were used to derive growth-related statistics.

It was shown that it is possible to measure individual tree height growth. From all the techniques used, the difference between the treetops of each tree (in 1998 and 2003) resulted in the highest R<sup>2</sup> value (0.68). The underestimation was 7 cm and the RMSE was 43 cm. When the cylinder size was reduced to half, the results using histogram-based growth improved and were almost as good as the maximum point method. The error and bias obtained for individual tree height growth were lower than those reported in an earlier study concerning field measurements of height growth (Päivinen et al. 1992)

New growth models, monitoring climate change (and perhaps post-Kyoto protocols), and large area forest inventories as strip-based sampling can be seen as real-life applications.

## 5 DIGITAL TERRAIN MODELS FOR FOREST INFORMATION EXTRACTION

### 5.1 Background of DTM

Kraus and Pfeifer (1998) developed a DTM algorithm based on distinguishing laser points into terrain points and non-terrain points using an iterative prediction of the DTM and weights attached to each laser point depending on the vertical distance between the expected DTM level and the corresponding laser point. Pyysalo (2000) developed a modified recursive classification method for DTM extraction, where all points within 60 cm vertical distance from the lowest expected ground level were included equally in the next DTM model calculation. Axelsson (1999, 2000, 2001) developed a progressive TIN densification method. Elmqvist (2001) estimated the ground surface by employing active shape models by means of energy minimization. Sithole (2001) and Vosselman and Maas (2001) developed a slope-based filtering technique, which works by pushing up vertically a structuring element. In the method by Wack and Wimmer (2002) non-terrain raster elements are detected in a hierarchical approach that is loosely based on a block-minimum algorithm. An empirical comparison of the methods is depicted in detail in Sithole and Vosselman (2004).

Kraus and Pfeifer (1998) reported an RMSE of 57 cm in wooded areas using ALTM 1020 and average point spacing of 3.1 m. Hyypä et al. (2000b) reported a random error of 22 cm for modulating forest

terrain using Toposys-1 and nominal pulse density of 10 pulses per m<sup>2</sup> using the method of Pyysalo (2000). Ahokas et al. (2002) compared three algorithms (including Pyysalo and Axelsson) in forested hill in Finland and found random errors between 13 and 41 cm using Toposys-1. Reutebuch et al. (2003) reported random errors of 14 cm for clearcut, 14 cm for heavily thinned forest, 18 cm for lightly thinned forest and 29 cm for uncut forest using TopEye data with 4 pulses per m<sup>2</sup>. However, in dense forests, errors up to 10 to 20 m can occur in the DTM estimation (Takeda, 2004).

The quality of DTM derived from laser scanning is influenced by a large number of other factors, the reader is referred to the introduction of Yu et al. (2005b). From the users point of view, the most relevant issues in the specifications of the data acquisition are date, point density, flight altitude and scan angle. According to Kraus (2004), point density is the most important parameter to explain the accuracy of the terrain model. In the assumption of Kraus (2004), the density was defined as the number of pulses on the ground, which is influenced by forest characteristics, beam size, and other parameters.

Therefore, this sub-study focused on factors affecting the DTM in boreal forest conditions, especially the effect of the date, flight altitude, pulse mode, forest cover and plot variation on the DTM accuracy. Details of the sub-study can be found in Hyypä, H. et al. (2005).

## 5.2 Methods

The accuracy of the laser DTM was evaluated by comparing the DTM values with the corresponding reference points obtained by field measurements. Systematic elevation error was calculated as mean height differences between laser DTMs and field measurements, whereas the random error was obtained from standard deviation (STD) of the difference.

## 5.3 Results

### 5.3.1 Effect of the Date

The random errors varied from test site to test site. With the last pulse, the measurements conducted during leaf-off period resulted in the smallest random error, i.e. 7-17 cm, in most of the plots. The use of a non-optimal season resulted in increased random error by 3 to 9 cm (units). In general the differences were smaller than expected. Plot 14 has dense undergrowth and hence all date resulted in inferior performance. Plot 30 has dense high vegetation (mixed species), which was more difficult during leaf-on period.

Figures 7 and 8 show the random error of the DTM derivation using first and last pulse.

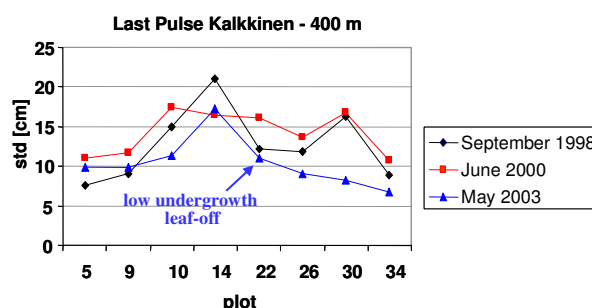


Figure 7. The effect of the date on the DTM random error using last pulse.

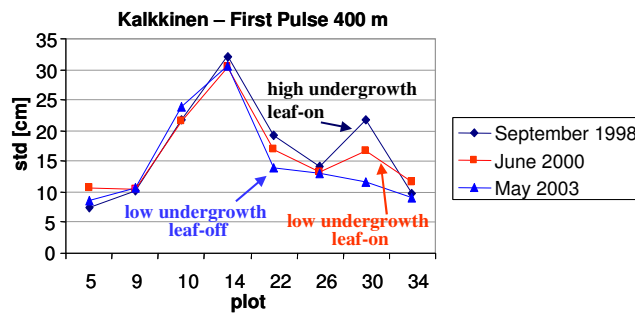


Figure 8. The effect of the date on the DTM random error using first pulse.

Even with the first pulse and with non-optimal season the obtained results were good.

### 3.3.2 Effect of Flight Height

By increasing the flight altitude, the density of the pulse decreases in the across-track direction. From the altitudes of 400, 800 and 1500 m, the across-track point spacings were 0.80, 1.6 and 3.0 m, respectively. The corresponding beam sizes on the ground were 0.4, 0.8 and 1.5 m. Therefore, the effect of the flight altitude is a combined effect of the across-track point spacing reduction and increase in the beam size. Figure 9 summarizes the results.

With Toposys II (i.e. acquisition done in 2003), the first and last pulse modes were acquired simultaneously. The systematic shifts with respect to ground references are shown in Figure 9. At 400 m, the first pulse overestimated DTM approximately 9 cm compared to the last pulse. In 800 m, the difference was 4 cm, and at 1500 m, the difference was  $-1$  cm. This is most likely due to the effect of the beam size and sensitivity. At 400 m, the small beam more easily finds the undergrowth at first pulse. The small pits are also found if the system is sensitive enough. With a larger beam and from a higher altitude (lower return pulse level), the difference between the first and last pulse decreases.

The random errors obviously increase as flight altitude increases. This is mainly due to the decrease of the pulse density and increase in the planimetric error (for non-flat surface).

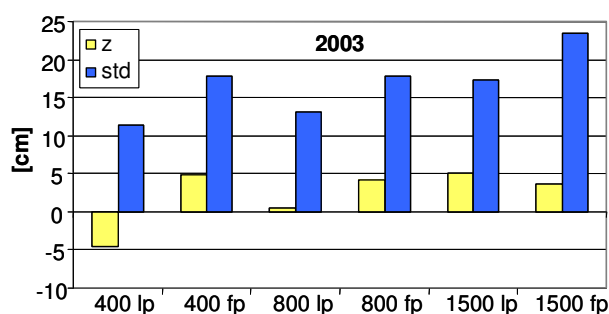


Figure 9. The DTM systematic and random errors from different flight altitudes at first and last pulse modes.

It can be concluded that the effect of the first versus last pulse on the errors is higher than doubling the flight altitude. The effect is approximately the same as making the flight altitude four times as high. An impressive random error of approximately 18 cm was obtained for hilly boreal forest area (relatively dense concerning forest cover) from the height of 1500 m with the last pulse.

### 5.3.2 Effect of Forest Cover

In order to evaluate the effect of forest cover on DTM derivation accuracy, tree-cover effects were examined. All plots were segmented into small regions corresponding to either open areas (no vegetation above) or under tree areas. Also the DTM beside the trunk was measured.

The effect of forest cover is higher when moving closer to the trunk. The maximum systematic difference due to the cover is 8 cm in the 400 m last pulse datasets. The random error increases 2 to 3 cm under the tree and it is 2-5 cm higher near the trunk with the last pulse, which indicates that the ground elevation can be reliably detected even under trees. With the first pulse, see the analysis in Yu et al. (2005b).

### 5.3.3 Within Plot Variation

Within plot variation is mainly caused by the variation in the terrain slope, undergrowth and vegetation cover. Figure 10 shows both systematic error and random error variation analyzed for example plots.

The results show that the systematic error variation is higher than the random error variation. The former is caused by changes in undergrowth, remaining errors in strip orientation and problems in the calibration of the elevation level. For example, for the test plot number 9, which is fairly smooth with gentle slope, the systematic error range between -18 to 11 cm, where-as the random error (with all flight altitudes and pulse modes and dates) ranges from 7 to 11 cm. Systematic error variation was higher than the random error variation except for the test site 14, which includes dense undergrowth and steep slopes.

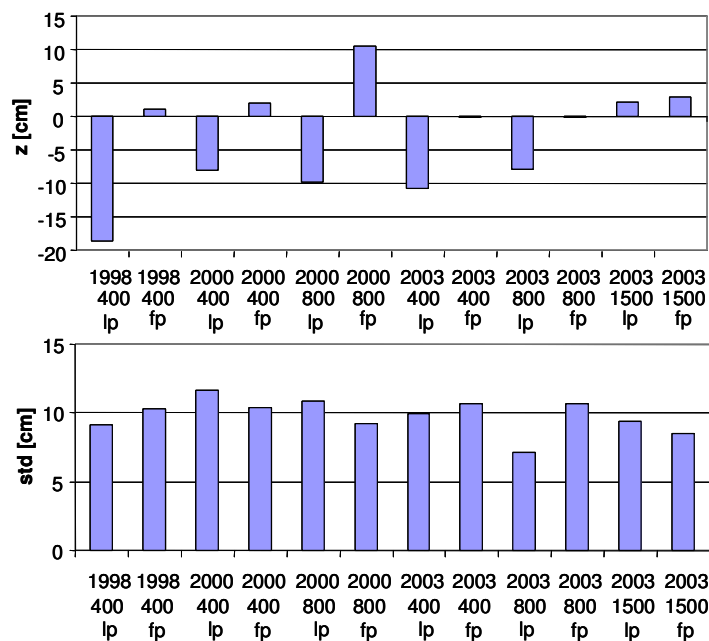


Figure 10. Within systematic (top) and random (below) plot variation for plot 9.

### 5.4 Conclusions

The following conclusions could be drawn from the high-density data:

- At boreal forest zone, random errors of less than 20 cm can be obtained in most conditions for non-steep terrain.
- The increase of flight altitude from 400 to 1500 m increased the random error of DTM derivation from 12 to 18 cm (i.e. 50%).
- The difference of using first or last pulse causes a corresponding random error difference, i.e. 5 cm.

- There are systematic shifts in the elevation models derived at various flight altitudes. It is expected that the beam size and sensitivity of the laser system cause this systematic behaviour. Additionally, the systematic shifts between last and first pulse are significant.
- The difference in DTMs derived at optimum and non-optimal season conditions is typically less than 5 cm –for high-density data (this is not relevant for most applications). In stand consisting of deciduous trees, the effects are the highest. Use of non-optimal flying season mainly causes that details of the terrain elevation can not be measured in the same accuracy.
- The effect of forest cover is higher when moving closer to the trunk. The random error is 2-5 cm higher.
- The results are site dependent, i.e. the accuracy varies as function of site conditions (slopes, undergrowth, forest cover).

## 6 CONCLUSIONS

For detailed conclusions see each sub-study and their conclusions in 3.5, 4.4 and 5.4. The major findings of the paper are summarized as follows

- Four improved inventory techniques, which are either more cost-effective or robust than pure distribution based or individual tree based techniques, were proposed.
- The use of various techniques to measure individual tree height growth was demonstrated. Differences between DSMs, height histograms and the highest laser hits were used to derive growth-related statistics. The error and bias obtained for individual tree height growth were lower than those reported in an earlier study concerning field measurements of height growth (Päivinen et al. 1992). New growth models, monitoring climate change (and perhaps post-Kyoto protocols), and large area forest inventories as strip-based sampling can be seen as real-life applications.
- From the practical inventory point of view the results on DTM accuracy imply that the flight parameters have a small effect on the precision of the DTM, but the systematic differences needs to be understood and taken into account. The most problematic areas are dense deciduous canopies or canopies with dense underground vegetation. In other areas, the applied algorithms have a negligible effect on DTM retrieval. Thus, also more automatic techniques may be used for terrain model calculation. In Yu et al. (2005b) it was also shown that in boreal forest zone the use of first pulse results in accuracy enough for forest studies due to the high amount of gaps for laser pulses in boreal forests.

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