

**METHODS AND TECHNIQUES FOR FOREST CHANGE  
DETECTION AND GROWTH ESTIMATION USING  
AIRBORNE LASER SCANNING DATA**

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## ABSTRACT

Airborne laser scanning has been used increasingly for extracting and estimating forest parameters. Experiences in Nordic countries and Canada have shown that retrieval of stem volume and mean tree height on a tree or stand level from laser scanner data performs as well as, or better than, photogrammetric methods, and better than other remote sensing methods.

The increasing interest in laser data for forestry applications has led to the present research, which quantifies forest growth and detects possible changes over time using repeated multi-temporal laser surveys over boreal forests. For the thesis, methods and techniques were developed for detecting change automatically and estimating forest growth using multi-temporal airborne laser scanning. The performance of these methods was evaluated based on the field measurements consisting of individual trees or sample plots. All the component studies were carried out in boreal forest at a test site in southern Finland.

For the detection of change, e.g. harvested or fallen trees, an automatic method was developed based on the image differencing technique applied to digital canopy height models generated from laser data from different dates. New scientific approaches developed for height and volume growth estimation were the individual tree-top differencing method, digital surface differencing and canopy height distribution based analysis. In the individual tree-top differencing method, growth estimation was based on individual tree identification and a tree-to-tree matching algorithm. The digital surface differencing method was based on the difference image of digital surface models. In the analysis based on canopy height distribution, growth was determined as a function of the difference in corresponding percentiles of the canopy height distribution between different laser acquisitions. These methods can be applied at both the individual tree level and the plot/stand level.

The findings reported in this thesis indicated that multi-temporal airborne laser scanner data can be used for estimating or predicting growth and detecting harvested area and fallen trees with an acceptable level of accuracy (an RMSE of less than 0.5m for individual tree height growth, a standard deviation of about 6.7 m<sup>3</sup>ha<sup>-1</sup> (26.8%) for volume growth and 0.15 m for mean height growth, and a detection accuracy of 80% for harvested trees). The methods developed could be used to complement field measurements, to improve predictions from a growth model and to develop new-generation forest growth models.

**Key words:** *airborne laser scanning, DTM, CHM, DSM, tree height, individual tree, change detection, height growth, volume growth, canopy height distribution.*

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Xiaowei Yu

## LIST OF PUBLICATIONS

This thesis is based on the following papers, referred to in the text by their Roman numerals:

- I. Hyypä, J., Hyypä, H., Leckie, D., Gougeon, F., Yu, X. and Maltamo, M., Review of methods of small-footprint airborne laser scanning for extracting forest inventory data in boreal forests. *International Journal of Remote Sensing*, in press.
- II. Yu, X., Hyypä, J., Kaartinen, H. and Maltamo, M., 2004. Automatic detection of harvested trees and determination of forest growth using airborne laser scanning. *Remote Sensing of Environment*, 90:451-462.
- III. Yu, X., Hyypä, J., Kaartinen, H., Hyypä, H., Maltamo, M. and Rönholm, P., 2005. Measuring the growth of individual trees using multi-temporal airborne laser scanning point clouds. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI(Part 3/W19) pp 204-208 (CD-ROM).
- IV. Yu, X., Hyypä, J., Kukko, A., Maltamo, M. and Kaartinen, H., 2006. Change detection techniques for canopy height growth measurements using airborne laser scanning data. *Photogrammetric Engineering and Remote Sensing*, 72(12):1339-1348.
- V. Yu, X., Hyypä, J., Kaartinen, H., Maltamo, M. and Hyypä, H., Obtaining plotwise mean height and volume growth in boreal forests using multitemporal laser surveys and various change detection techniques. *International Journal of Remote Sensing*, in press.

Paper III is a peer reviewed conference paper.

In general, the division of work between others and myself was the following. I was responsible for practically all data processing and analysis, and for the actual realization and improvement of methods. I was the main author of papers II-V. Professor Juha Hyypä was my supervisor, providing the initial ideas for papers, and he also participated constantly in brainstorming with me on ideas and methods, and in writing the papers to varying degrees. Harri Kaartinen M.Sc. was responsible for the field references. Professor Matti Maltamo acted as the forest science expert concerning all the papers and Docent Hannu Hyypä was an additional laser scanner expert. Matti and Hannu both provided me with comments, advice and improvements for the papers, and consequently could be considered co-supervisors of my thesis. In addition, Petri Rönholm and Antero Kukko assisted me briefly during the process.

#### Paper I

My contribution was as co-author, concentrating especially on change detection. Juha Hyypä was the author responsible for writing the paper.

#### Paper II

My role was the processing, analysis and most of the writing. The research was supervised by Juha Hyypä. Harri Kaartinen carried out the field surveys to test the performance of the method. Matti Maltamo was the advisor on forest inventory.

#### Paper III

I carried out most of the work from preparing the data to testing the method and the necessary computer coding. Juha Hyypä was the supervisor of the study. Harri Kaartinen conducted the field measurements of individual tree height and growth. Hannu Hyypä and Matti Maltamo were advisors. Petri Rönholm created the image with laser points projected onto an optical image taken of the same object.

#### Paper IV

I carried the main responsibility for implementing the methods, and carrying out the scientific research. Juha Hyypä was the supervisor of the study. Antero Kukko provided the initial code for tree-to-tree matching and some of the computations. Matti Maltamo was the forest inventory expert and Harri Kaartinen organized and carried out the field measurements.

#### Paper V

I carried out most of the work involved in the paper. Juha Hyypä supervised the research. Harri Kaartinen organized and carried out most of the field measurements. Matti Maltamo and Hannu Hyypä were advisors.

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## LIST OF ABBREVIATIONS

ALS	Airborne laser scanning
AVHRR	Advanced Very High Resolution Radiometer
CARABAS	Radar system operating at low frequencies
CHM	Canopy height model
DBH	Diameter at breast height (1.3 m above ground)
DEM	Digital elevation model
DGPS	Differential global positioning system
DSM	Digital surface model
DTM	Digital terrain model
ERS	European Remote Sensing Satellite
ETM	Enhanced Thematic Mapper
GIS	Geographic information system
GPS	Global Positioning System
ICP	Iterative closest point algorithm
IKONOS	A commercial earth observation satellite
IMU	Inertial Measurement Unit
INS	Inertial navigation system
INSAR	Interferometric Synthetic Aperture Radar
IRC-1C	Indian Remote Sensing satellite
JERS	Japanese Earth Resources Satellite
NOAA	National Oceanic and Atmospheric Administration
PAN	Panchromatic band of satellite imagery
PRF	Pulse repetition frequency
RMSE	Root mean squared error
SAR	Synthetic aperture radar
SEASAT	The first satellite designed for remote sensing of the Earth's oceans with synthetic aperture radar
SPOT	Satellite Pour l'Observation de la Terre
TIN	Triangulation irregular network
TM	Thematic Mapper
VHF	Very high frequency

## 1. INTRODUCTION

### 1.1 Background

Forests are living ecosystems influenced by continuous natural and anthropogenic processes. Monitoring changes in the forest cover and canopy structure through time is important for many applications, such as decision-making (Zimble *et al.*, 2003), forest planning and management (Sironen *et al.*, 2001), climate change studies (Nuutinen and Kellomäki, 2001; Justice *et al.*, 2001; Matala, 2005), and wildlife habitat (Coops and Catling, 1997). The ability to measure forest and monitor change in forested areas at regular intervals and in a cost-effective manner is thus becoming increasingly important.

Forest can be characterized by its attributes (parameters, features, variables). The basic attributes for a tree or a stand include height, diameter at breast height (DBH), species, age, location, basal area, volume, biomass, and leaf area index. Some of these can be directly measured or calculated from measurements, while others need to be estimated (predicted) using statistical or physical modelling. This information describes the state of development of forests.

Measurement and mapping of forest have been typically carried out through forest inventories. Inventories can be made at various levels and scales from regional to national or for a small area unit. Different emphases can be put on different aspects, depending on the purpose of the inventory. Traditional forest inventories have relied upon aerial photography interpretation and ground-based sampling. Thanks to the development of remote sensing technologies over the past 35 years, there are now systems that provide alternative approaches and a more automatic and efficient way for collecting data and measuring forests in terms of both cost and time. Forest change can be established either by detecting actual forest and land use change or by executing an inventory twice over the same area (Varjo and Mery, 2001; Chapman *et al.*, 2006). Methods based on remote sensing normally utilize the former approach (Häme, 1988, 1991), while national forest inventories typically use the latter.

Airborne laser scanning (ALS) is an active remote sensing technique that provides three-dimensional (3D) high precision measurements of targets based on laser ranging combined with use of a differential Global Positioning System (DGPS) and an Inertial Measurement Unit (IMU) (Baltsavias, 1999; Wehr and Lohr, 1999). Rapid technical advances currently make ALS one of the most promising technologies for the retrieval of detailed information about forest at different levels, i.e. from the individual tree to the plot/stand. In Norway, laser scanning has been used operationally in large area inventories since the early years of this decade (Næsset *et al.*, 2004). Inventory at tree level is currently at the pre-operative stage in Scandinavia.

Changes in the forest can be caused by nature, e.g. insect or disease damage, or by anthropogenic factors, e.g. thinning or clearing. The rate of change may be abrupt (e.g. logging) or subtle/gradual, e.g. growth and seasonal variations. This thesis focuses on forest growth estimation, i.e. height growth at the individual tree, plot and stand level and volume growth at the plot level, and harvested trees detection.

## 1.2 Objectives

The primary objective of the research, conducted during 2001-2006, was to develop algorithms and techniques for forest change detection using multi-temporal high-density small-footprint laser scanning data, and to evaluate the performance of the methods developed. Prior to this work, no research had been done on change detection using laser scanning for forest purposes. The emphasis was on the development of algorithms and methods. The specific aims of the studies were:

- to develop algorithms and techniques for detecting forest changes caused by tree removal and tree growth;
- to evaluate the performance of the methods and techniques developed with regard to the height growth of individual trees and mean height and volume growth at plot level;
- to develop a tree to tree matching algorithm for linking the tree detected from different laser acquisitions;
- to assess the most predictive variables for growth estimation.

## 1.3 Hypothesis

The basic hypotheses of the studies were as follows:

- Determination of individual tree growth is possible if the same trees in different acquisitions can be linked automatically.
- It is possible to develop an intelligent and automatic object-to-object matching technique which allows object-based comparisons between images and allows growth analysis based on individual tree identification.
- Individual tree detection is possible using high-density small-footprint ALS data.

## 2. TECHNIQUES AND METHODS FOR FOREST MEASUREMENTS

### 2.1 Conventional Field Measurements

Traditionally, information on trees, such as their height, diameters at different heights along the stem and crown diameter, are measured in the field. The conventional strategy for collecting such data is a plot-wise field inventory specifically by measuring the diameters, because diameter is convenient to measure and is one of the directly measurable dimensions from which tree cross-sectional area, surface area and volume can be computed. Various instruments and methods have been developed for measuring tree dimensions in the field (Husch *et al.*, 1982; Päivinen *et al.*, 1992; Gill *et al.*, 2000; Korhonen *et al.*, 2006): calipers, diameter tapes and optical devices for diameter measurements; level rods, poles and hypsometers for tree height measurements; and an increment borer for diameter growth measurements. The method used in obtaining the measurements is largely dictated by the accuracy required.

Sometimes it is necessary to fell the tree to obtain more accurate measurements, such as the only way to actually measure the stem volume is through destructive sampling of a tree. As a result, direct and indirect methods have been developed for the estimation of such variables. Examples of volume estimation methods include the graphical method, in which a cross-section area at different heights along the trunk are plotted over height on paper, the area under the curve being equivalent to the volume, and the use of volume equations which estimate volume through the relationship with measurable parameters such as height and/or diameter at breast height.

The accuracy of field measurements is usually high at a point level. Päivinen *et al.* (1992) reported that DBH could be measured with a stand deviation ranging from 2.3 mm to 4.6 mm and height could be measured with a stand deviation of 67 cm.

It is widely recognized that obtaining forest information through ground measurements is time-consuming and costly (Pouliot *et al.*, 2002; Holmström *et al.*, 2003). At the same time, demands for the collection of both up-to-date and more detailed information are increasing. This is compelling foresters to look for more cost-effective alternatives or supportive methods for field survey.

## **2.2 Methods Based on Remote Sensing Techniques**

Remote sensing techniques, both passive and active, have been widely and actively used for extracting forest parameters and detecting changes. The aim is to obtain forest variables at the lowest possible cost, yet providing accurate estimates over a large area. Well-known methods include interpretation in aerial photographs (e.g. Anttila, 2002; Korpela and Takola, 2006), digital classifications and analysis of optical satellite images (e.g. Walsh, 1980; De Wulf *et al.*, 1990; Tomppo *et al.*, 2002), and backscatter modelling of radar data. As technology advances, new methods are being developed all the time to cope with higher spatial and spectral resolutions (Johnsson, 1994; Shackelford and Davis, 2003), new data types (e.g. Næsset, 1997a,b; Hyypä and Inkinen, 1999; Hoffman *et al.*, 2001) and a combination of different data sources (e.g. Gong, 1994). A comprehensive review of remote sensing techniques in forestry can be found in Leckie (1990), Wulder (1998) and Boyd and Danson (2005).

In the following, the methods used for forest measurement based on remote sensing are described separately, depending on their data characteristics and the techniques applied.

### **2.2.1 Aerial photography and digital images**

Since the late 1920s, aerial photographs and more recently digital/digitized aerial images have been used in forestry as a tool to support the monitoring and management of forest resources and as an integral part of most forest inventory procedures. The approach has been used in a variety of ways to determine the dimensions, form, volume, growth and species of trees. Of the information desired on trees and stands, tree height (Kovats, 1997; Næsset, 2002b; Gong *et al.*, 2002), crown counts (Dralle and Rudemo, 1996; Lowell, 1998), crown diameter (Brandtberg and Walter, 1998; Pouliot *et al.*, 2002; Gong *et al.*, 2002), crown shape (Gong *et al.*, 2002) and forest types or species (Bliss *et al.*, 1980; Meyer *et al.*, 1996; Key *et al.*, 2001) can all be obtained directly from aerial photographs. Other information, such as stem diameter,

basal area, tree volume and stand volume, is obtained through a process of correlation with the former characteristics (Husch *et al.*, 1982). Substantial effort has gone into finding a way of using photographs as a means of determining volume (Holmström *et al.*, 2001; Anttila, 2002; Tuominen and Pekkarinen, 2005). Today, airborne photography is still the main data source for forest mapping and forest parameter derivation in many countries (see e.g. Holmgren, 2003). The extraction of information from aerial photographs traditionally utilized a visual interpretation method based on colour, shape, texture and context information. However, automatic methods were also proposed along with the development of digital camera and digital photogrammetric techniques. A review of aerial photograph used for vegetation attribution determination was published by Fensham and Fairfax (2002).

The accuracy of stand attribute measurements made from aerial photographs has been studied in the context of visual stereo interpretation. The standard errors in volume estimation varied from 28% to 54% (Nyyssönen, 1955; Poso, 1983; Pussinen, 1992; Anttila, 2002). Eid and Næsset (1998) reported that standard errors in volume estimation in practical photo inventories varied between 10.5% and 33.6%.

### 2.2.2 Satellite optical remote sensing methods

Since the launch of the first earth observation satellite, the usefulness of various types of optical satellite image data for forest applications has been widely studied. Coarse spatial resolution AVHRR/NOAA images have been used most commonly for mapping forest and detecting land cover changes on the regional or global scale (e.g. Colwell and Hicks, 1985; Mayaux *et al.*, 1998; Franklin and Wulder, 2002; Packalén *et al.*, 2006). Medium spatial resolution Landsat/TM and SPOT data were demonstrated to be more suitable for vegetation classification and the forest mapping of larger-area and stand-level attribute derivation (e.g. Walsh 1980; Cohen and Spies, 1992; Bauer *et al.*, 1994; Trotter *et al.*, 1997; Tomppo *et al.*, 2002). More recently, high-resolution satellite data such as IKONOS have proved useful in stand-level inventory (e.g. Nelson *et al.*, 2004; Chubey *et al.*, 2006) or even information at individual tree level (e.g. Key *et al.*, 2001; Gougeon and Leckie, 2006). Satellite spectral data are typically related to the forest attributes via various vegetation indices, classification, bidirectional reflectance modelling, individual tree isolation and spectral mixture analysis of single data.

The accuracy of stand attributes derived from medium spatial resolution satellite images was usually low compared with aerial photo interpretation or field measurements of the same variables. For example, Poso *et al.* (1999) reported volume RMSEs of 73% - 81% with Landsat-5 TM imagery and 71% - 74% with IRS-1C PAN imagery. Franco-Lopez *et al.* (2001) reported volume RMSE of approximately 65% in the USA (Minnesota). Tuominen and Haakana (2005) reported a volume RMSE of 74.5% for Landsat ETM imagery. Hyypä and Hyypä (1999) reported a standard error of 27.7% for stand height with TM imagery and 28.33% with SPOT multispectral imagery; for stand volume estimates, a standard error of 44.5% with TM images and 37.7% with SPOT multispectral images was also reported.

### 2.2.3 Radar

Active synthetic aperture radar (SAR) is the sensor type which images volumes of vegetation rather than reflectance from the surface of the canopy. The transmitted microwave radiation penetrates the vegetation canopy to a depth depending on the wavelength and polarization (Balzter *et al.*, 2003). The imaging processing makes SAR suitable for mapping parameters related to forest biomass, such as stem volume. Furthermore, SAR works in almost all weather conditions (Bovolo and Bruzzone, 2005).

Forest attributes are usually determined with statistical regression techniques or physical modelling to relate the backscatter, coherence or interferometric of SAR/INSAR with forest attributes such as tree height or volume (Pulliainen *et al.*, 1994; Israelsson *et al.*, 1997; Balzter *et al.*, 2002; Santos *et al.*, 2003; Askne and Santoro, 2005; Santoro *et al.*, 2005).

Several authors (Askne *et al.*, 1997; Fransson and Israelsson, 1999; Kurvonen *et al.*, 1999; Koskinen *et al.*, 2001; Santoro *et al.*, 2002; Fransson *et al.*, 2004) have reported promising methods for forest stem volume and tree height retrieval using space-borne multitemporal ERS-1 and JERS-1 SAR images in a boreal forest, using L-band backscatter and coherence, C-band coherence (especially from ERS-1/2 Tandem mission) and backscatter. An overview of the performance of satellite-based SAR for standwise forest inventory is given in Hyyppä *et al.* (2000a), indicating poor quality for practical forestry.

Studies with airborne SAR have also shown some capabilities for forest attributes retrieval. Hyyppä (1993) and Hyyppä *et al.* (1997) demonstrated the feasibility of a non-imaging helicopter-borne ranging scatterometer for standwise forest inventory. The radar-derived stand profiles were compared with the standwise field inventory data by applying multivariate data analysis methods. The accuracy of the radar-derived estimates for mean height was 1.6 m (13%) meeting the requirement for operational use. The 31 m<sup>3</sup>/ha (26%) stem volume accuracy obtained was slightly better than that obtained using aerial photographs. Smith and Ulander (2000) presented a physical model describing the backscatter from coniferous boreal forests in the lower VHF-band in terms of stem volume. When measurements of mean amplitude (rather than intensity) are used in high-resolution SAR images, a linear dependence on stem volume can be obtained. The model fits well with the measurements made using the coherent all-radio-bands sensing (CARABAS) SAR in boreal forest, indicating the possibility of retrieving stem volume, and hence biomass, with an accuracy similar to that achieved by standard ground-based measurements. Fransson *et al.* (2000) developed and evaluated regression models predicting forest parameters from airborne CARABAS-II VHF (20-90 MHz) SAR backscattering amplitudes. The results showed a linear relationship between backscattering amplitude and forest stem volume, stem diameter and tree height. The RMSEs in the regression analysis, restricted to forest stands on near-horizontal ground, were found to be 66 m<sup>3</sup>/ha, 3.2 cm, and 2.3 m for stem volume, stem diameter and tree height respectively. No saturation of the backscattered signal was observed up to the maximum stem volume of 625 m<sup>3</sup>/ha, corresponding to a biomass of 375 tons/ha. In addition, single-pass airborne interferometric SAR has been used for tree height estimation (Izzawati *et al.*, 2006), and polarimetry SAR interferometry (Papathanassiou *et al.*, 2000; Cloude and Corr, 2003), and tomography

SAR (Reigber *et al.*, 2005) has been used to create tree height information from forest.

#### **2.2.4 Airborne laser scanning**

Over the past few years, ALS has become a very important technique in various forest applications, such as generation of high quality digital terrain model (DTM) in forested area (Kraus and Pfeifer, 1998; Vosselman, 2000), studies of forest structure (e.g. Hyypä and Inkinen, 1999; Persson *et al.*, 2002) and forest dynamics (St-Onge and Vepakomma, 2004).

Techniques for forest parameter retrieval with ALS can basically be divided into two groups, one based on canopy height distribution analysis (Næsset, 2002a; Lim *et al.*, 2003; Holmgren, 2004) and the other based on individual tree detection (Hyypä and Inkinen, 1999; Persson *et al.*, 2002; Popescu *et al.*, 2003; Leckie *et al.*, 2003). In the former method, quantiles of the distribution of laser canopy heights are used as predictors to estimate forest characteristics. If the number of laser pulses is increased, e.g. to a couple of measurements per square metre, individual trees can be recognized (Hyypä and Inkinen, 1999; Persson *et al.*, 2002; Popescu *et al.*, 2003; Leckie *et al.*, 2003; Brandtberg *et al.*, 2003). From individual trees, the height, crown diameter and tree species are then derived using ALS and possibly with aerial image data. A comparison of optical airborne and spaceborne instruments and laser scanning can be found in Hyypä and Hyypä (1999), prompting confidence about the future of ALS in forests.

#### **2.2.5 Automatic terrestrial measurements**

Side by side with airborne and spaceborne remote sensing methods, rapid technological development has made terrestrial laser measurements a complementary way of performing accurate forest measurements. Terrestrial laser scanners are capable of recording sample plots with extremely high accuracy (Watt *et al.*, 2003; Hopkinson *et al.*, 2004; Thies and Spiecker, 2004; Thies *et al.*, 2004), but are not yet practicable because of the high cost of data processing and the large volume of data. However, this is a potential way of establishing changes in stems in future. At the moment, automatic terrestrial measurements can be seen as complementary techniques for operative standwise forest inventory; they provide an accurate reference for developments in airborne remote sensing but do not replace the need for airborne data over large areas.

#### **2.2.6 Combined use of techniques**

All the techniques described above have their advantages and disadvantages. The use of multi-source data provides the potential for more accurate forest mapping by integrating the various different features of the data. For example, studies have shown that combined use of multi-temporal data and multi-source data can improve the prediction accuracy of forest attributes (Kurvonen *et al.*, 1999; Lefsky *et al.*, 2001). Holmgren *et al.* (2000) have shown that the estimation accuracy for small-area stem volume increases when information on tree height is used in combination with satellite image data. Tree height information can be extracted from ALS data or from aerial stereo measurements. ALS data have been used with aerial images for forest inventory

(Holopainen and Talvitie, 2004; Packlén and Maltamo, 2006), as sampling tools (Tickle *et al.*, 2001) and to estimate individual tree heights (Suarez *et al.*, 2005). The basic idea is to utilize the merits of each system to achieve the optimum solution. Development of methods for multi-scale image analysis and multi-source data applications pose a great challenge because the data come from different sources and sensors, with different resolutions and geometry. The knowledge-based system is one advanced approach that can handle multi-source data. In most cases, data from different sources are processed separately at an early stage, and the combined use takes place at a later stage of the procedure.

Comparison of various data sources for the estimation of forest attributes can be found in Hyypä *et al.* (2000a) and Lefsky *et al.* (2001). It is evident that ALS is a feasible technique for predicting forest variables (Hyypä and Hyypä, 1999; Hyypä *et al.*, 2000a; Lefsky *et al.*, 2001; Hudak *et al.*, 2006).

### **3. TECHNIQUES AND METHODS FOR FOREST CHANGE DETECTION**

Forest changes are caused by three types of forces: internal growth and evolutionary development, natural forces and human induced harvest and forest management (Gong and Xu, 2003). Forest change, such as growth, cutting, can be detected either by executing field inventories at regular time intervals or by finding actual forest and land use changes using remote sensing techniques.

#### **3.1 Conventional Field Measurements**

Determination of tree growth is most commonly obtained by means of repeated measurements at the beginning and end of a specified period, when the difference equals the growth (Husch *et al.*, 1982; Uzoh and Oliver, 2006). Better tree measurements are required when the interest is in growth over time rather than size at a particular moment. Estimates of height increment are usually satisfactory if the height is measured using height sticks, but may be unsatisfactory if measured using a hypsometer (Husch *et al.*, 1982). Estimates of diameter increment are much more reliable, particularly if the point of measurement on stems is marked permanently. Past growth in diameter can be obtained from increment borings or cross-section cuts (Poage and Tappeiner, 2002). Past height increment can be determined by stem analysis (Uzoh and Oliver, 2006). In species for which the internodal lengths on the stem indicate a year's growth, past height growth can be determined by measuring the internodal lengths (Husch *et al.*, 1982). In principal, only past growth can be measured in these ways, but it is future growth that is usually of interest and this has to be predicted using a growth model (Hynynen, 1995; Hökkä and Groot, 1999; Hall and Bailey, 2001; Matala, 2005).

The accuracy of field measurements is usually high. Päivinen *et al.* (1992) reported that 5-year height increment of Scots pine and Norway spruce was measured with a standard deviation of 27 cm and 20.5% in the estimate of volume increment for a 65-year-old Scots pine stand.



## 3.2 Methods Based on Remote Sensing Techniques

Change detection using remote sensing techniques normally involves two procedures: change extraction (change detection algorithm) and change separation/labelling (change classification) (Coppin *et al.*, 2004). A variety of automatic techniques have been developed (Hudak and Wessman, 1998; Hyppänen, 1999; Bruzzone and Prieto, 2002; Saksa *et al.*, 2003; Lu *et al.*, 2004; Im and Jensen, 2005; Miller *et al.*, 2005). They can be grouped broadly into two categories: simultaneous analysis of multi-temporal data, and comparative analysis of independently produced classifications according to Singh (1989). Both approaches can be applied on a pixel-to-pixel basis or on an object-oriented basis. In the former method, the multi-temporal data is analysed simultaneously using methods such as multi-date classification, image differencing, or principal component analysis. In the latter method, the classifications of images for different dates are compared and changes in land cover are detected. A review of change detection techniques using remote sensing data can be found in Singh (1989), Lu *et al.* (2004) and Coppin *et al.* (2004).

Usually, change detection involves the analysis of two or more remote sensing images (multi-temporal data) acquired over the same geographical area at different times. To allow for the comparison between the series of data at the same location, a geometric correction should be undertaken to register the data to real world coordinates or to each other. For optical multi-temporal data, radiometric correction is also required to remove the influence of e.g. viewing geometry and atmospheric conditions on image radiances (Holopainen and Jauhiainen, 1999).

Optical remote sensing imagery has been the dominant data source for change detection, so most methods have been developed for optical images. In principle, the procedure designed for optical spectral data can be applied to the analysis of radar imagery and ALS data. However, there are differences in the data characteristics, leading to differences in the handling of radar and ALS data.

### 3.2.1 Aerial photography and digital images

Repetitive acquisitions of aerial photographs have been used for forest change detection (Holopainen and Jauhiainen, 1999; Kadmon and Harari-Kremer, 1999; Fensham and Fairfax, 2002; Saksa *et al.*, 2003; Hyvönen and Anttila, 2006; Jauhiainen *et al.*, 2007). Kadmon and Harari-Kremer (1999) used digitized aerial photographs of a mountainous landscape dominated by Mediterranean maquis in northern Israel over a period of 32 years in order to study landscape-scale, long-term vegetation cover changes. Their change detection method comprised pixel-level classification, the results being averaged to larger cells and the cell values differenced. Saksa *et al.* (2003) demonstrated the applicability of high-altitude aerial photographs for detecting the clear-cut areas in boreal forest. Their change detection was based on image differencing performed at different levels and the results showed that the methods and data were accurate enough for operational detection of clear-cut areas. In Hyvönen and Anttila (2006), a semi-automatic method based on bi-temporal aerial photographs taken in 2001 and 2004 was developed to detect the changes caused by operations and forest damage. Stepwise discriminate analysis was used for change classification based

on 110 features extracted at stand level. The overall accuracy of classification varied between 75.3% and 84.7% and the best accuracy was obtained by using histogram and texture features. A review of aerial photograph used for assessing vegetation change was published by Fensham and Fairfax (2002).

Aerial photography has certain advantages over other optical remote sensing techniques for long-term change detection, e.g. it allows 3D measurements for the accurate estimation of tree and canopy, and data series can span 60-70 years (Fujita *et al.*, 2003; Korpela and Tokola, 2006; Korpela, 2006) although the analyses were normally carried out in 2D using monoscopic mode. With 3D measurements, a series of digital surface models (DSM) of forest canopy can be created and can be used to determine subtle changes such as tree growth as a function of time (St-Onge *et al.*, 2004), assuming that they have been properly calibrated.

### 3.2.2 Satellite optical remote sensing methods

When time-series data are available, the change in the forest can be detected using various change detection techniques (e.g. Ahern, 1991; Coops and Waring, 2001; Donoghue *et al.*, 2004). The advantage of the daily availability and low cost of NOAA/AVHRR has made it an invaluable source for large-area change detection. For example, NOAA/AVHRR have been used to monitor vegetation temporal changes (Batista *et al.*, 1997) and to detect forest fires (Cuomo *et al.*, 2001). Coppin and Bauer (1994) presented digital procedures for optimizing the information content of multi-temporal Landsat TM data sets for forest cover change detection. Their results show that the relationship between reflective TM data and forest canopy change is explicit enough to be of operational use in a forest cover change stratification phase, prior to more detailed assessment. Wilson and Sader (2002) developed a simple and relatively accurate technique for classifying time-series Landsat TM imagery to detect levels of forest harvest. Whiffen *et al.* (2000) used Landsat TM data from both leaf-on and leaf-off time periods to predict the variation in basal area over southeast United States of mature loblolly pine stands and found that the spatial resolution of the Landsat TM's sensors was insufficient to accurately distinguish variations in basal area data at the 30 metre plot scale.

### 3.2.3 Radar

SAR has been less exploited than optical sensors in the context of change detection because of the intrinsic complexity of SAR data (Bazi *et al.*, 2005; Bovolo and Bruzzone, 2005). Despite this, the use of SAR in change detection is potentially attractive from the practice viewpoint as they are independent of atmospheric and sunlight conditions. Balzter *et al.* (2003) used repeated SAR observations (L-band) from SEASAT and JERS-1 to estimate the incremental tree growth of Corsican pine stands over 19 years. Two methods were developed in their study to relate the changes in the backscatter coefficient to the growth; one was to derive growth by estimating top height from SAR images and taking the height difference, and the other was to estimate tree growth from temporal backscatter change directly by using an empirical model. An RMSE of 8.2 m was obtained for tree growth by the first method and 3.4 m by the second, using a linear model.

### 3.2.4 Airborne laser scanning

Change detection using ALS has not been studied extensively before the present thesis. Today, the techniques used for detecting change in forest and urban areas can be grouped as analysis based on canopy height distribution (Næsset and Gobakken, 2005), object identification (Vögtle and Steinle, 2003; St-Onge and Vepakomma, 2004), and image differencing (Murakami *et al.*, 1999; Steinle and Bähr, 2002; Thuy *et al.*, 2004). The changes detected are harvested trees, forest gap dynamics, urban/building change and height and volume growth.

### 3.2.5 Combined use of techniques

Combined use of different techniques can take the advantage of each technique. Sometimes this is the only way to detect changes over a long time period because it may be difficult to obtain data using the same instrument because of constant advances in technology. For examples, Kress *et al.* (1996) studied forest cover loss during the period 1935 to 1987, using data derived from aerial photography, historical map products and Landsat satellite multi-spectral imagery. ALS data have been used with aerial images to improve classification for change detection (Haala and Walter, 1999; Walter, 2004), to map forest canopy height changes (St-Onge and Achaichia, 2001). Development of methods for change detection using multi-scale and multi-source data is a more challenge task because the geometric and radiometric corrections between different source data are more demanding than single source data.

## 4. STATE OF THE ART OF LASER SCANNING

### 4.1 Laser Scanning Principle

Airborne laser scanning techniques, also referred to as airborne lidar, provide a number of new possibilities for the remote sensing of forest. It has become a widely accepted technique that has the capability to measure height and height-related attributes. As an active remote sensing technology, laser scanning can provide direct three-dimensional measurements of the forest canopy structure and underlying terrain surface based on laser ranging, a differential Global Positioning System (DGPS) and an Inertial Measurement Unit (IMU) (Baltsavias, 1999; Wehr and Lohr, 1999). A typical ALS system can be subdivided into the following key units: a laser ranging unit, an opto-mechanical scanner, a position and orientation unit, and a control and processing unit (Wehr and Lohr, 1999; Hollaus, 2006). For the range measurements, two different principles are applied, i.e. the pulse range and the phase difference measurement. Only the pulse ranging principle is described here because it is commonly used in an ALS system. When a laser pulse was emitted from a laser ranging unit, the return time for it to travel between sensor and target is measured, providing the distance from the instrument to the object. The location of each return is achieved by precise kinematic positioning using a DGPS and orientation parameters obtained by an IMU, these being the two main components of the position and orientation unit. Laser scanning is realised by the opto-mechanical scanner by

deflecting the transmitted laser pulse across the flight path. Different ALS systems use different scanning mechanisms (e.g. an oscillating mirror, rotating polygon, multifaceted mirror, fibre scanner, nutating mirrors), resulting in a different scan pattern on the ground (see, e.g. Hollaus, 2006). The motion of the aircraft, in combination with the deflection of the laser pulse across the flight path, generates strip-wise measurements of the illuminated area. Figure 1 illustrates the principle of ALS.

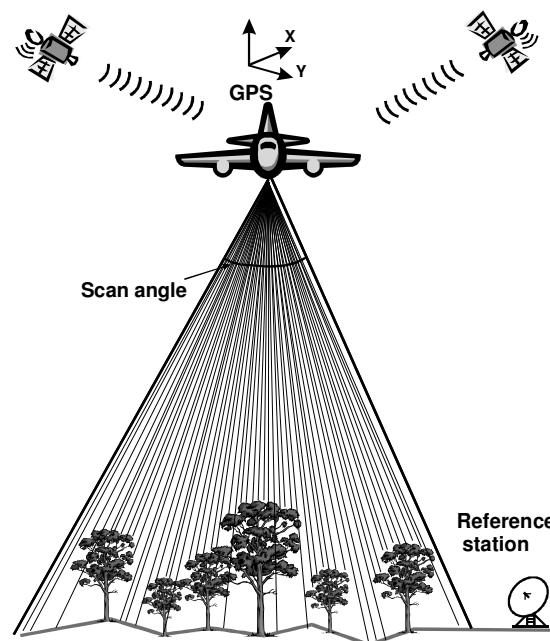
Due to the laser beam divergence, the emitted signal typically illuminates an area along the pulse path. Reflections might occur at different elevation levels and for different objects when laser pulse travels along the path. For instance, a hit on a tree might lead to returns from branches at different heights, resulting in multiple returns.

Consequently, one must decide which return should be referred to as the measurement; this is called the measurement mode of the laser scanning (Steinle and Bähr, 2002). On the other hand, successful separation of two neighbouring objects along the pulse path requires a minimum distance between the objects, which is determined by the pulse duration. The size of the footprint is determined basically by the flight altitude and beam divergence. It is one of the most important characteristics of ALS data and is capable of influencing the accuracy of derived DTM and forest attributes. Another characteristic is the pulse (point or sampling) density (number of measurements per unit area), which is determined by the pulse repetition frequency, flight speed, maximum scan angle and altitude.

Most modern laser systems have the ability to record multiple returns per pulse. The first returns are supposed to be reflected mainly from the forest canopy but also from the ground, and the last returns from the vegetation and ground in more detail. There are also systems that record a digitized full form of the returns (waveform). With the ability to vary the scan angle, scan frequency and operating altitude, these systems can be tailored to a wide array of application needs based on the area to be covered and the required measurement density. (Evans *et al.*, 2006).

Laser scanner systems differ in

- 1) footprint size, from small footprint (< 1 m), medium footprint (1 to 25 m) to large footprint (> 25 m)
- 2) numbers of returns, from one to several returns (discrete system) or a full waveform (waveform system) being recorded for each pulse emitted
- 3) sampling rate (density).



**Figure 1.** Measurement principle of laser scanning. (after Hyypä and Inkinen, 1999).

In this thesis, a small footprint and high sampling density data (about 10 points/m<sup>2</sup>) with two returns (first and last) were used. Table 1 lists the main characteristics of the laser scanning system used in this thesis.

**Table 1.** TopoSys-I/-II performance parameters.

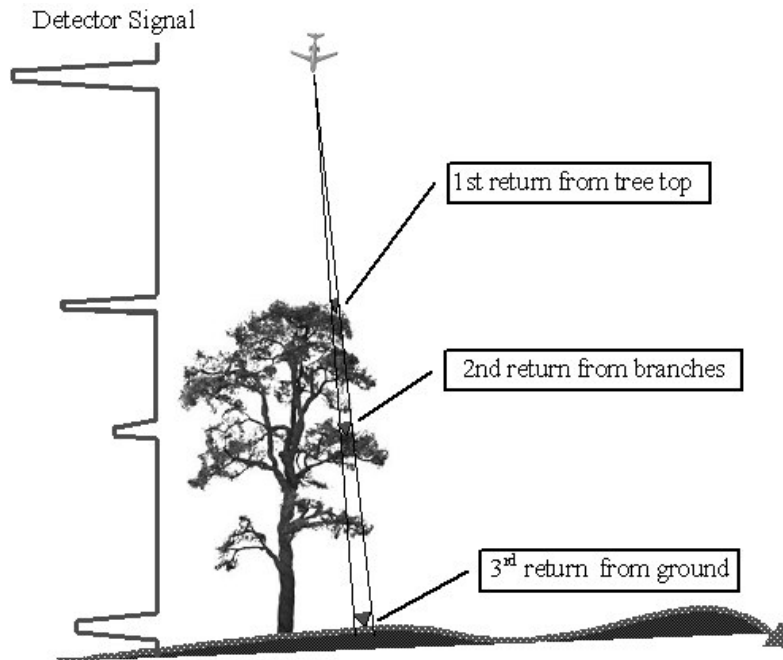
<b>Parameter</b>	<b>Performance(s)</b>
Sensor	pulse-modulated
Laser pulse frequency	83 000 Hz
Scan frequency	653 Hz
Field of view	± 7.1 degrees
Measurement density	Ca. 5 pulses per m <sup>2</sup> at 800 m Ca. 10 pulses per m <sup>2</sup> at 400m
Beam divergence	1 mrad
Number of shots per scan	128 parallel shots (one of which is the reference)
Laser classification	class 1 by EN 60825 (eye-safe)

## 4.2 Interaction of Laser Beam with Forest

Using the reflection of an emitted signal to measure distances to the sensor is ambiguous. A measurement of this kind can only be definite if the whole signal is reflected homogeneously, i.e. if the signal is reflected as a whole and reaches the sensor again at one definite time point. However, it is more likely that there is a degree of signal division due to inhomogeneous reflectance (Steinle and Bähr, 2002). In the case of a laser pulse hit on forest canopy, the reflectance can be simple or complex. Theoretically, in the simplest case a laser pulse may be scattered directly from the top of a very dense vegetation canopy, resulting in a single return. Since forest canopy is not a solid surface, the situation can become more complex. If there are gaps in the canopy cover, the laser pulse may hit the canopy and pass through the top, intercepting with different parts of the canopy such as the trunk, branches or leaves before reaching the ground. This series of events may result in several returns being recorded for a single laser pulse, this being called ‘multiple returns’ (Figure 2). In most cases, the first and last returns are recorded because the first return is assumed to come mainly from the top of the canopy and the last one mainly from the ground, which is important for extracting the terrain surface. Multiple reflections of laser pulses can produce useful forest information, particularly on height.

Trunks, branches and leaves in dense vegetation tend to cause multiple-scattering reflections or absorption of the emitted laser energy, so that fewer backscattered returns are reflected directly from the ground (Harding *et al.*, 2001; Hofton *et al.*, 2002). This effect increases with greater canopy closure, depth and structural complexity because the laser pulse is greatly obscured by the canopy. In practice, the laser system specifications and configurations can also play an important role in how laser pulses interact with forest. Findings include the following: a small footprint laser tends to penetrate the tree crown before reflecting a signal (Gaveau and Hill, 2003); ground returns are decreased as the scanning angle increases (TopoSys, 1996); penetration rate is affected by laser beam divergence (Aldred and Bonnor, 1985; Næsset, 2004); a difference in flight altitude alters the distribution of laser returns from

the top and within the tree canopies (e.g., Næsset, 2004); the distribution of laser returns through the canopy varies with a change in laser pulse repetition frequency (PRF) (Chasmer *et al.*, 2006). Furthermore, the sensitivity of the laser receiver and its wavelength, the laser power and total backscattering energy from the tree tops are other factors that may influence the ability of laser pulses to penetrate and the distribution of laser returns from forest canopy (Baltsavias, 1999).



**Figure 2.** Interaction of the laser pulse with forest canopy, resulting in multi-returns.

### 4.3 Laser Scanning of Forest

The use of ALS for forest applications has increased significantly in the past few years due to its ability to determine tree and stand parameters such as tree height, volume, stand density and biomass, and the accuracy achieved. Tree height is one of the most important parameters in forest analysis. It is also one parameter that can be directly measured with laser scanning. ALS-based forest measurements basically rely on generation of a DTM and DSM corresponding to the treetops from laser points.

#### 4.3.1 Digital terrain model

With the ability to penetrate forest canopies, ALS was first developed as a technique for the acquisition of an accurate digital terrain model, especially in forested areas where traditional techniques such as photogrammetric stereo measurements often failed. Algorithms have been developed for the generation of DTMs (Kraus and Pfeifer, 1998; Axelsson, 1999, 2000; Vosselman, 2000; Elmqvist *et al.*, 2001). These are either

iterative statistical based or morphological based. Using these methods, laser points reflected from the ground were separated from points reflected from other objects such as buildings and trees, based on the assumption that the lowest returns in a small neighbourhood will be ground. This labelling procedure is called classification or filtering. For example, Kraus and Pfeifer (1998) used an iterative prediction procedure which gave weights to each laser point, depending on the vertical distance between the expected DTM level and the corresponding laser point. A comparison of the filtering techniques used for DTM extraction can be found in Sithole and Vosselman (2004). The classified ground points can then be used to generate a DTM in a TIN or grid model. In the latter case, an interpolation is normally involved.

The accuracy of the DTM achieved in forested areas depends on the laser data characteristics, such as pulse density, first/last pulse mode, flight height, scan angle (Ahokas *et al.*, 2005; Hyypä *et al.*, 2005a), characteristics of the complexity of the target, such as the terrain type, the density of the canopy above (Raber *et al.*, 2002a; Hodgson *et al.*, 2003) and the methods used for classification and interpolation, as well as on forest characteristics such as the species and density (Raber *et al.*, 2002a). Test flights (TopoSys, 1996) have shown that at scanning angles of more than 10 degrees off-nadir, the amount of shadowed areas increases greatly, i.e., the number of measured ground hits decreases and gaps in the DTM occur more frequently. With respect to type of terrains and surfaces, Raber *et al.* (2002a) and Hodgson *et al.* (2003) found that land-cover types were a significant factor that influences the accuracy of a laser DTM in forested areas. Terrain slope impact on laser DTMs were examined by Hyypä *et al.* (2000b) and Hodgson *et al.* (2003). Raber *et al.* (2002a) suggested that when information about the terrain type or land cover is available, it can be used in the filtering to improve the accuracy of the resulting DTM. In addition, data obtained in leaf-off conditions were found to be more suitable for mapping the terrain surface than data obtained in leaf-on conditions (Raber *et al.*, 2002b). In Hyypä *et al.* (2005a) and Yu *et al.* (2005), the accuracy of DTMs derived from laser scanner data in boreal forests were evaluated. The impact of the forest type and the effect of flight altitude, acquisition date, return pulse mode, interpolation errors, terrain slope and scanning angles on the accuracy of the DTM were also investigated. The results showed that there are systematic shifts in the elevation models derived at various flight altitudes (400 m, 800 m and 1500 m). The use of first or last returns for DTM generation results in comparable random errors and a small systematic upwards shift of the order of 10-20 cm in the first return DTM compared with use of the last returns. The difference in DTMs derived in optimal and non-optimal seasonal conditions is typically less than 5 cm for high-density ALS data.

Results from these earlier studies suggest that greater accuracy was obtained in open flat areas. With an increase in vegetation cover or terrain slope, accuracy deteriorated. It seems that forest canopy and understorey vegetation cover are among the major factors that affect the accuracy of laser DTMs in forested areas by preventing a larger proportion of laser pulses from hitting the underlying ground. Studies have shown that the terrain is often overestimated in forested areas (Kraus and Pfeifer, 1998; Reutebuch *et al.*, 2003; Clark *et al.*, 2004). This is caused by the ground vegetation, because it is not always possible to separate ground hits from the ground vegetation hits.

### 4.3.2 Canopy height model and canopy height

A measurement of canopy height can be obtained from the first returns and ground returns in a procedure referred to as 'normalization'. There are two ways to do this. One is to create a raster DSM by taking the highest point within a defined pixel size and interpolating the missing points, e.g. using Delaunay triangulation, and then a canopy height model (CHM) can be obtained by subtracting the corresponding DTM from the DSM. The other method is to subtract the underlying ground elevation from the laser returns, resulting in normalized heights, also referred to as canopy heights. A CHM can then be created from the canopy heights in the desired pixel size. The corresponding terrain elevation values can be interpolated from the classified ground returns. Tree height is normally retrieved from either the CHM or the canopy height. The CHM greatly reduces the volume of laser data and also allows for the application of standard raster GIS and remote sensing algorithms and software (Leckie *et al.*, 2003; Suarez *et al.*, 2005).

Tree height and vertical distribution of the canopy are the variables that can be directly measured from the CHM or canopy heights. Other variables can be modelled or inferred from these direct measurements. If individual trees can be identified, the crown dimension can be measured, too.

Most studies provide evidence that tree height is underestimated with laser data (Hyypä and Inkinen, 1999; Persson *et al.*, 2002; Lefsky *et al.*, 2002; Gaveau and Hill, 2003; Leckie *et al.*, 2003; Clark *et al.*, 2004; Maltamo *et al.*, 2004; Chasmer *et al.*, 2006; Falkowski *et al.*, 2006). According to all these studies, it seems that underestimation of tree height is caused by the following: the density and coverage of the laser pulses; the algorithm used to obtain the canopy height model; the amount and height of undervegetation; the algorithm used to calculate the DTM; the sensitivity of the laser system and the thresholding algorithms used in the signal processing; the pulse penetration rate; and the tree shape and tree species.

Gaveau and Hill (2003) indicated that a small-footprint laser pulse hitting the upper surface of a canopy often advanced into the canopy before reflecting a detectable first return signal and that this penetration of the upper canopy by each laser pulse varied with small-scale variation in the closure of the upper canopy surface and with variations in leaf area, density, reflectivity and orientation. Accurate estimation of the CHM or canopy height depends on a good approximation of the ground level underneath. Studies have shown that the terrain is often overestimated in forested areas (Kraus and Pfeifer, 1998; Reutebuch *et al.*, 2003; Clark *et al.*, 2004). As a result, the canopy height is decreased further. Missing tree tops due to insufficient sampling density and small footprint size (Aldred and Bonnors, 1985; Dubayah and Drake, 2000; Evans *et al.*, 2001; Lefsky *et al.*, 2002) are also one reason why tree height is underestimated. According to Lefsky *et al.* (2002) the sampling density is the principal issue determining the likelihood of canopy height underestimation with small-footprint laser data. In Yu *et al.* (2004), the effect of system parameters, e.g. flight altitude, sampling density and beam size, on the tree height estimation was evaluated at individual tree level using laser data from 400 m, 800 m and 1500 m altitudes. The results indicated that tree height was underestimated in all cases. The estimation accuracy and number of detectable trees decreased as the flight altitude increased. The increase in point density resulted in a slight increase in the accuracy of the tree height



estimates. Tree height was found to be less affected by the footprint size, and it seems that point density has more influence on tree height estimation. Birch was less affected than coniferous trees by the changes in flight altitude.

Finding a universal correction factor for such underestimation may be difficult, however, since the correction appears to be dependent on the sensor system, flight altitude, forest type and the algorithm used. Gaveau and Hill (2003) used a terrestrial laser system to calibrate the underestimation, whereas Rönholm *et al.* (2004) demonstrated the use of terrestrial image data in calibration of the effect. Magnussen and Boudewyn (1998) introduced a geometrical model that successfully predicted the mean difference between the laser canopy heights and the mean tree height.

### 4.3.3 Extraction of forest attributes

ALS data have been demonstrated to be useful for the determination of forest parameters. There are two main approaches in deriving forest information from laser scanner data, one based on statistical canopy height distribution and the other based on individual tree detection. In the distribution-based techniques, features and predictors are assessed from the laser-derived surface models and canopy-height point clouds, and incorporated with the field measurements to drive stand or plot level estimates typically using regression or discriminant analysis. In the individual tree based approaches, the neighbourhood information of canopy-height point clouds and pixels in DSMs or CHMs are effectively used to derive physical features and measures, such as crown size, individual tree height and location. The forest inventory data are calculated or estimated using existing models and statistical techniques, or a compilation of individual tree information. A good review of ALS data for forest applications can be found in Næsset *et al.* (2004).

#### *Distribution-based method*

Height percentiles of the distribution of canopy heights have been used as predictors in regressions and models for the estimation of mean tree height, basal area and volume (e.g. Lefsky *et al.*, 1999a,b; Magnussen *et al.*, 1999; Means *et al.*, 2000; Næsset, 1997a,b; Næsset and Økland, 2002; Næsset, 2002a; Lim *et al.*, 2002; Hopkinson *et al.*, 2006). In Means *et al.* (2000), height percentiles and canopy cover percentiles were used in the estimation of tree height, basal area and volume in forests dominated by Douglas fir, with tree heights ranging from 7 to 52 m, and a coefficient of determination values of 0.93, 0.95 and 0.97 were obtained, respectively. Næsset and Økland (2002) used canopy height percentiles to predict mean tree height with a standard error of 7.6% (1.5 m). In Næsset (2002a), several forest attributes were estimated using canopy height and canopy density metrics, using a two-stage procedure and field data over young and mature forest stands. Metrics derived from canopy height distribution included the quantiles corresponding to the 0, 10, . . . , 90 percentiles of the distributions, the maximum values, the mean values, the coefficients of variation and several measures of canopy density. Canopy densities were computed as proportions of first pulse laser hits above the 0, 10, . . . , 90 quantiles of the first pulse height distributions to the total number of first pulses. The standard deviations of the differences between the predicted and ground-truth values of mean height and

dominant height were 0.61 - 1.17 m and 0.70 - 1.33 m, respectively. Similarly, in Hall *et al.* (2005), 39 metrics were derived from the lidar data and used to estimate stand height, canopy base height, tree density, basal area, crown bulk density, and total aboveground and foliage biomass in low-density forests.

The same method also provided estimates for basal area and stand volume. In Næsset (2002a), basal area and volume were estimated with standard deviations of 8.6% - 11.7% (2.33 - 2.54 m<sup>2</sup>/ha), and 11.4% - 14.2% (18.3 - 31.9 m<sup>3</sup>/ha), respectively, using canopy height and canopy density metrics and a two-stage procedure in a boreal forest. In forest dominated by Douglas fir in the western Cascades, Oregon, Means *et al.* (2000) estimated both stem volume and basal area using percentiles of canopy height distribution combined with the canopy cover percentile calculated as the proportion of first return below a given percentage of total height. Regression models produced an R<sup>2</sup> of 0.97 and 0.95 for stem volume and basal area respectively.

#### *Method based on individual tree detection*

One key characteristic of ALS data is the pulse density, which is determined by the flight altitude, flight speed, maximum scan angle and pulse repetition frequency. An improvement in pulse repetition frequency allows for denser sampling. When the pulse density of laser data increases to more than 2-4 points/m<sup>2</sup>, individual tree crowns can be sampled. Several image analysis methods have been developed for the detection of individual trees using high- and very-high-resolution aerial imagery (Dralle and Rudemo, 1996; Brandtberg and Walter, 1998; Gougeon, 1995; Pouliot *et al.*, 2002; Erikson, 2003). The methods used in ALS have merely been adopted from these studies. In ALS, the aerial image is replaced by the crown DSM or the canopy height model.

The extraction of individual trees can be divided into finding tree locations, finding tree locations with crown size parametrization, or full crown delineation. Tree locations can be found by detecting the local maxima of images (Dralle and Rudemo, 1996; Wulder *et al.*, 2000). After finding the local maxima, the edge of the crown can be found using region segmentation, edge detection, or local minima detection (Pinz, 1991; Uuttera *et al.*, 1998). Full crown delineation is also possible with techniques such as shade-valley-following (Gougeon, 1995), edge curvature analysis (Brandtberg and Walter, 1999), template matching (Pollock, 1994; Larsen and Rudemo, 1998), region growing (Erikson, 2003) or 3D clustering (Morsdorf *et al.*, 2003). In laser scanning, the delineation can result in what is called full individual tree crown isolation, since the upper top of the crown will be fully modelled in 3D. This approach permits tree counts, tree species, crown area, canopy closure, gap analysis, and volume or biomass estimation (Gougeon and Leckie, 2003). For example, tree location, height and crown size can be determined directly from individual tree delineation, and stem diameter and volume can be estimated based on the linear regression or existing allometric equations, with height and crown diameter or estimated stem diameter as explanatory variables.

Hyypä and Inkinen (1999) demonstrated that high-density laser measurement was useful for detecting individual trees and for deriving characteristics such as tree height, location and crown diameter. Using the CHM local maximas for tree finding and segmentation for edge detection, 40% to 50% of coniferous trees could be correctly segmented. The tree height of the dominant storey was obtained with a standard error

of less than 1 m. Crown diameter and tree height were related to stem diameter by means of an empirical model. Estimated stem diameter and laser-measured tree height were then used as input to volume function for individual tree volume estimation. Mean tree height and stem volume were evaluated at stand level with a standard error of 13.6% and 9.5% of the respective mean values. The accuracy obtained satisfied the requirements of operational standwise forest inventory.

Persson *et al.* (2002) created a digital canopy model using an active contour algorithm applied from the top of the canopy instead of low-pass filtering to remove the pulses that had penetrated the vegetation. The digital canopy model was further smoothed by 2D Gaussian filters with different scales. The appropriate scale in different parts of the image is determined by fitting a parabolic surface to the canopy model. Based on the smoothed image, local maxima were identified and the crown was delineated. Evaluation with field measurements showed that 71% of the tree heights could be linked with the reference trees, representing 91% of the stem volume. Tree height and crown diameter were estimated with an RMSE of 0.63 m (2.6%) and 0.61 m (12%), respectively.

Brandtberg *et al.* (2003) presented a method for individual tree detection using high-density lidar data acquired in a deciduous forest in the eastern USA in leaf-off conditions. Segmentation of individual trees was carried out based on a three-dimensional scale-space structure created by Gaussian smoothing at different scales. The results indicated that the species of individual trees can be classified with a moderate to high degree of accuracy (40% - 60%) and tree height estimated with a 1.1 m standard error for 48 sample trees.

Popescu *et al.* (2003) used the local maximum technique to locate trees from a lidar data set acquired over deciduous, coniferous and mixed stands of varying age classes and settings typical of the southeastern United States. The results for estimating crown diameter were similar for both pines and deciduous trees, with  $R^2$  values of 0.62–0.63 for the dominant trees (RMSE 1.36 to 1.41 m). The measured crown diameter improved  $R^2$  values for volume and biomass estimation by up to 0.25 for both pines and deciduous plots. (RMSE improved by up to 8 m<sup>3</sup>/ha for volume and 7 Mg/ha for biomass.) For the pine plots, the average crown diameter alone explained 78% of the variance associated with biomass (RMSE 31.28 Mg/ha) and 83% of the variance for volume (RMSE 47.90 m<sup>3</sup>/ha).

Morsdorf *et al.* (2004) demonstrated a segmentation method using cluster analysis on the lidar raw data in all three coordinate dimensions over a site forming part of the Swiss National Park. Tree position, height and crown diameter are derived from the segmented clusters and compared with field measurements. A robust linear regression of 917 tree height measurements yields a slope of 0.96 with an offset of 1 m and an adjusted  $R^2$  of 0.92.

#### **4.3.4 Change detection and forest growth by laser scanning**

Most forest changes are caused by disturbances such as climate change, flooding, fire, insects and diseases, harvesting, clear cutting and thinning. Forest growth, on the other hand, is a natural process consisting of elongation and thickening of roots, stems and branches. Growth causes trees to change in weight and volume and in form (Husch *et al.*, 1982). Trees grow in height through the elongation of the tips of their branches,

but diameter growth is centred in the trunk. Usually, only the growth of the tree stem is considered by using the growth characteristics of the tree. In most cases, volume growth is the most interesting characteristic and it has to be derived from the change observed in other characteristics.

The changes in forests that affect the laser scanning response include the vertical and horizontal growth of crowns, the seasonal change of needle and leaf masses, the state of undergrowth and low vegetation, and the trees moving with the wind (especially for taller trees). Thus, the monitoring of growth using ALS can be relatively complicated in practice. The technique applied should be able to separate growth from other changes in the forest, especially those due to selective thinning or naturally fallen trees. Changes can be detected either from temporal images derived from ALS data using standard change detection techniques, for example differencing of two elevation data sets to determine volumetric differences, or from temporal features using feature-based approaches (Armenakis and Savopol, 2004). No studies had been published on change detection in forest using ALS before work on this doctoral thesis began.

## 5. RESULTS AND SUMMARY OF PAPERS

### 5.1 Study Area and Data Materials

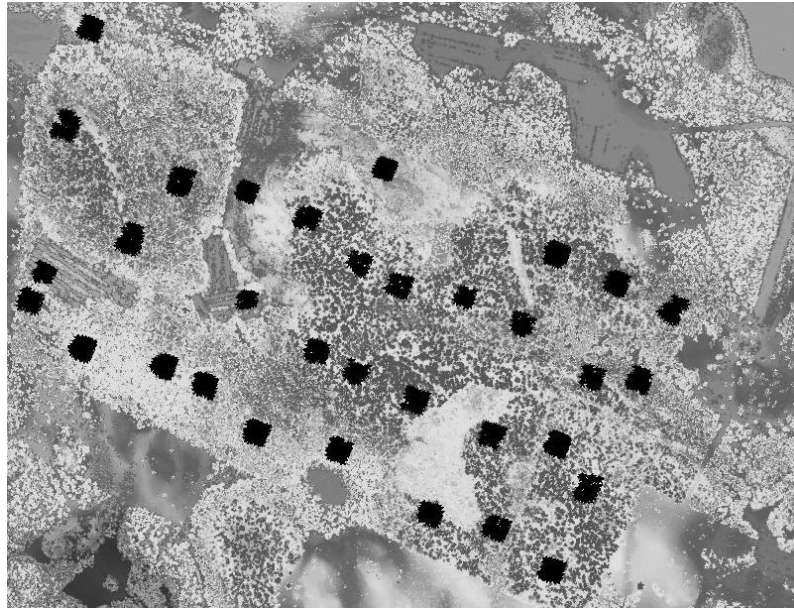
**Study area** – The 1.5 km by 2 km test area for the research conducted in this thesis is located in Kalkkinen, 130 km north of Helsinki, in southern Finland. Situated about 110 m above sea level, the test site is dominated by small hills and the main tree species are *Picea abies* (Norway spruce) (49%), *Pinus sylvestris* L. (Scots pine) (35%), *Betula verrucosa* and *Betula pubescens* (silver and downy birches) (11%). The average size of the stands was 1.2 hectares and their delineation was based on an earlier operational forest inventory.

**Laser data** - The laser data used in the studies were acquired with TopoSys-I in September 1998 and June 2000 and with TopoSys-II in May 2003. All were from an altitude of 400 m over the test area resulting in a nominal point density of 10 points/m<sup>2</sup>. The survey altitude was selected in order to provide enough measurements to permit the resolution of individual trees. The major difference between TopoSys-I and -II was that the latter permitted the simultaneous recording of the first and last returns. Both the first and last returns were recorded. A beam divergence of  $\pm 0.5$  mrad produced footprint diameters of 0.4 m. There are small gaps in 1998 coverage and only about half of the area is covered by 2000 survey.

**Field measurements of sample plots** - On the test site, 33 systematically distributed sample plots were established in 2001 (Figure 3), each about 30 m x 30 m. Within the plots, all trees with a DBH of more than 5 cm were mapped, and the tree species, DBH, tree height and height to the living crown were recorded. Furthermore, every tree was classified as belonging to either the dominant or the suppressed tree layer, using the classification of Kraft (see e.g. Assmann, 1970). Altogether 2690 trees were measured. Among them 1689 are dominant trees. The location of the trees was measured with a tacheometer. The coordinates of the four corners of the sample plots were determined by GPS measurements. It is expected that the corner points were measured with an accuracy better than 10 cm. In November 2004 and August 2005,

some of the sample plots were revisited to measure the DBH for the trees mapped in 2001. Altogether, there were 22 plots where DBH was measured in both 2001 and 2004/2005 and these were used for assessing laser-derived height and volume growth at plot level (Paper V).

**Field measurements of individual tree height and growth** – 153 pines were selected and their height, location and shoot elongation were measured in August 2002 and November 2004 for evaluating tree height growth (Paper III and IV). Three to six consecutive shoots below the top of the tree were measured. This gave the height of the tree after each annual growth period between 1998-2004. The measurements were made with a tacheometer or a rod to an accuracy of a few centimetres. In August 2002, measurements were concentrated on three plots (Paper II) and location information was lack for the most of the trees measured.



**Figure 3.** Study area (DSM derived from ALS data) and the location of field plots (black square).

## 5.2 Summary of Appended Papers

### **Paper I: Review of small-footprint airborne laser scanning methods for extracting forest inventory data**

There has been considerable research related to ALS for forest inventory purposes since the first experiments were conducted with the approach. A variety of methods have been developed for extracting forest information. This paper summarized and reviewed these methods and the quality of the forest inventory data extracted. The methods are divided into the following categories: extraction of a terrain and canopy height model; forest inventory techniques (canopy height distribution and individual

tree based techniques, techniques based on synergetic use of aerial images and ALS, and other new approaches); tree species classification using ALS; forest growth; and use of intensity and waveform data for forest information extraction. Research on forest inventory techniques using ALS data is still a topic of interest and new methods will continue to be developed for the effective use of 3D, waveform and intensity data. The paper therefore also proposes some subjects for future work.

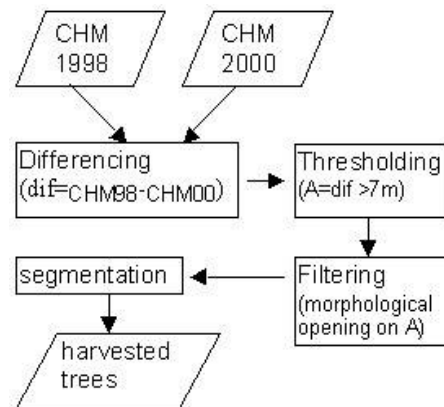
## Paper II: Change detection

This paper is the first to concern change detection in a forested area using multi-temporal laser data. The objective was to demonstrate the potential and applicability of small-footprint, high sampling density airborne laser scanners for boreal forest change detection, i.e. the estimation of forest growth and monitoring of harvested trees. An object-oriented algorithm was developed for detecting general changes and harvested and fallen trees from two laser acquisitions. Tree height growth was estimated based on individual tree delineation and a tree-to-tree matching algorithm. Performance was evaluated at plot level using three sample plots and demonstrated at stand level using twenty selected stands. Horizontal enlargement of the crown was also demonstrated at stand level.

Two laser acquisitions from 1998 and 2000 were available when the research was carried out and were used in the analyses. Three-dimensional canopy height models (CHM = DSM - DTM) were created separately for each acquisition using raster-based algorithms.

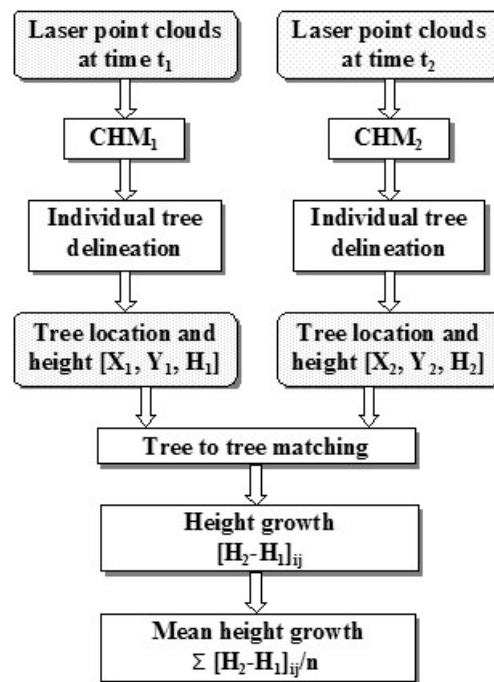
The automatic method developed and used for detecting harvested trees was based on image differencing techniques for change detection. A flowchart is shown in Figure 4. First, a difference image was created by subtracting the later CHM from the earlier one. The resulting difference image represented the pixel-wise changes between the two dates. Clustered high positive differences represented harvested trees (II: Figure 2). Most of the image value was close to zero (ground) or just below zero due to the tree growth. In order to identify harvested trees, a threshold was selected and applied to the different image in order to distinguish either no changes or minor changes from major changes. A morphological opening was then performed to reduce noise-type fluctuation. Finally, the location and number of harvested trees was determined based on segmentation of the resulting image.

The method for height growth estimation was based on individual tree delineation and a tree-to-tree matching algorithm. Individual tree delineation was performed on canopy height model images derived from both the 1998 and the 2000 acquisitions using commercial software (Arboreal Forest Inventory Tools of Arbonaut Ltd, Hyypä *et al.*, 2001a). First, trees were located by looking at the local maxima in the low-pass



**Figure 4.** Flow chart for harvested tree detection.

filtered canopy height model. Then, a watershed-type segmentation procedure was applied. During the segmentation processes, the tree crown shape and location of individual trees were determined. Each segment was considered to represent an individual tree crown. Each of the twenty stands was processed separately to get an optimum result. Tree heights were extracted from the canopy height model by taking the highest value of each corresponding tree segment. The location of the trees was defined as the location corresponding to the highest value of the segments. If the locations of two segments, one from each acquisition, were within a specified distance such as 0.5 m, which we called the threshold distance, then these two segments were considered a match. Matched trees were then used in growth estimation by taking the mean differences of the height for individual trees. The purpose of tree-to-tree matching is to eliminate the factors that could lead to false interpretations and to systematic errors in estimation, such as selective thinning and cutting after the first acquisition. Figure 5 illustrated the work flow in height growth estimation.



**Figure 5.** Work flow for mean tree height growth estimation.

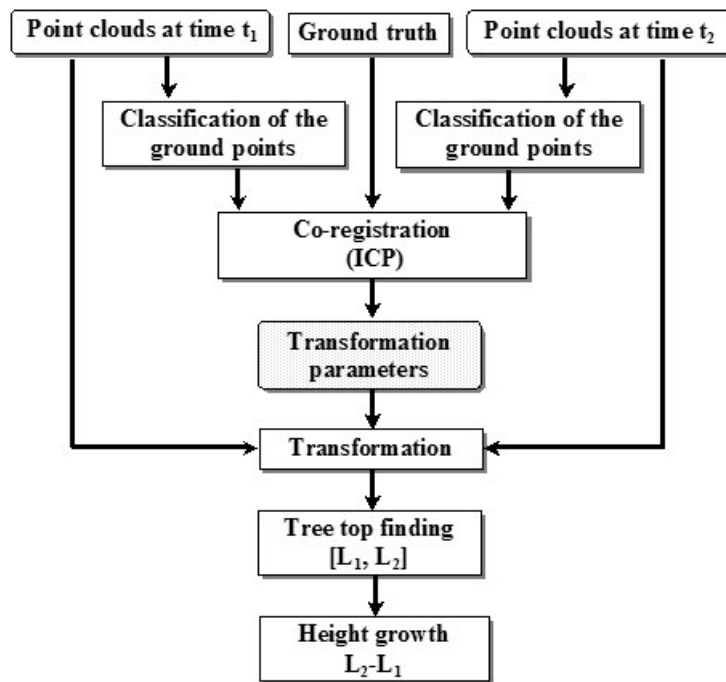
The results were very encouraging. Out of 83 field-checked harvested trees, 66 were automatically detected. All the mature harvested trees were detected, and it was mainly the smaller trees that caused problems. The precision of the estimated growth, based on field checking and/or statistical analysis, was about 5 cm at stand level and 10-15 cm at plot level. The obtained standard error of the mean agreed well with the field measurements. As the technique is developed and costs decrease, the methods presented in this study offer the possibility of replacing a large number of permanent plots in forest inventory with ALS techniques.

The results at plot level were improved when DEM error was compensated. This corresponds to a method in which DSMs are matched using flat surfaces and the growth is taken from the difference between them, instead of from the difference between CHMs.

### Paper III: Individual tree height growth estimation

It is well known today that heights of individual trees can be measured by ALS with an accuracy of 0.5 to 1.5 m. However, quality in individual tree growth estimation had not been reported earlier due to errors in tree height estimation, the slow growth rate of trees and difficulties in accessing high-density laser data enabling individual tree estimation. In this paper, the ability to measure the growth of individual trees using ALS is demonstrated and assessed. Methods for extracting the height growth of tree crowns automatically are presented.

Three acquisitions from 1998, 2000 and 2003 were available for use in the study. In the pre-processing of data, ground points were classified using TerraScan software and used for the co-registration of data acquired in different years. For the evaluation of tree height growth estimation using laser data, measurements of tree height and past 3-6 year growth of 153 pines were used as ground truth.



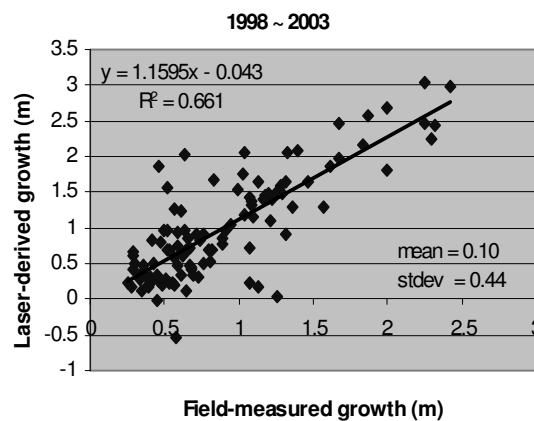
**Figure 6.** Work flow in individual tree height growth estimation.

In the analysis, the laser acquisitions were first registered to the same coordinate system in order to remove any systematic errors between different acquisitions, as this



is very important in change detection. Each acquisition was registered with ground truth (tacheometric measurements of the ground elevation for 2200 points in 8 plots) using classified ground points derived in the pre-processing. An iterative closest point (ICP) algorithm was used to calculate the shift in the x, y, and z direction. The results were then applied to all the laser measurements. A tree top finding was then performed based on the tree location information measured in the field, i.e. the treetop was sought in the close neighbourhood of the field-measured location. Afterwards, the corresponding laser points falling into a cylinder around the found location of each tree were used to extract the variables needed for growth estimation. The radius of the cylinder was determined on the basis of the relationship between tree height and crown width according to Pitkänen *et al.* (2004). The variable derived from the extracted points clouds was the maximum laser hit. The tree height growth was calculated as the difference between the maximum laser hits in two out of three laser acquisitions (Figure 6).

A good correlation was found between the laser-derived growth and field-measured growth in the 1998 and 2003 data sets ( $R^2 = 0.66$ ). The findings suggested that the height growth of individual trees can be measured with an accuracy better than 0.5 m. (Figure 7).



**Figure 7.** Scatter plot of field-measured growth vs. laser-derived growth.

#### **Paper IV: techniques for tree growth estimation**

The goal of this study was to develop techniques for tree growth estimation using multi-temporal airborne laser scanner data. Three methods are presented in the paper, i.e. comparison of canopy profiles, difference between DSMs (or CHMs) and analysis of the difference between height distributions. An advanced tree-to-tree matching algorithm based on Hausdorff distance was also developed to use in operational growth estimation based on individual trees. The methods developed for growth estimation were evaluated at individual tree level using 82 sample pines. For tree-to-tree matching, twenty selected sample plots were used to test performance.

Laser datasets acquired from two laser surveys conducted in September 1998 and

May 2003 were used in the study. The laser point clouds (X, Y, Z) were pre-processed as described in paper III.

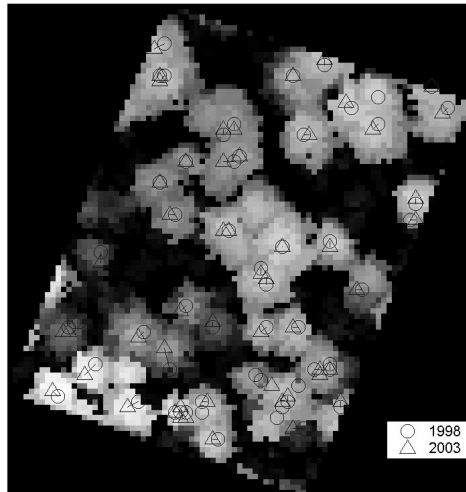
For each tree measured in the field, corresponding point clouds were extracted using the method developed in Paper III. Tree height growth was estimated with different techniques from the point clouds representing each tree. First, the highest laser height was taken from different laser surveys and the height growth was estimated as the difference between them for matched trees (IV: Plate 1). Secondly, the mean and median value of the difference between the DSMs of later and earlier acquisitions, and the difference between the means or medians of the DSMs were calculated and taken as the height growth. The DSMs were obtained by taking the highest point within each 50 cm grid (IV: Plate 2). Thirdly, the height histograms of the point clouds for each tree were formed and the 85th, 90th and 95th percentiles of the height canopy distributions were calculated (IV: Figure 1). The height growth was assumed to be the difference between the corresponding quantiles from different acquisitions for matched trees.

Tree-to-tree matching was performed using an improved algorithm based on Hausdorff distance (e.g. Beauchemin *et al.*, 1998) for finding the optimum tree pairs from different acquisitions. Hausdorff distance is the maximum distance between the point in one set and the nearest point in another set. More formally, the Hausdorff distance from set A to set B is a maximum function, defined as

$$h(A, B) = \max_{a \in A} \{ \min_{b \in B} \{ d(a, b) \} \}, \quad (1)$$

where a and b are the points of sets A and B respectively, and d (a, b) is any metric between these points in any dimension of space, e.g. the Euclidian distance between a and b. It should be noted that Hausdorff distance is oriented (asymmetric), which means that most of the time h(A, B) is not equal to h(B, A). This asymmetry is a property of the maximum function. Thus, the Hausdorff distance is a method of calculating the greatest minimum distance between two point sets using any metric. We can exploit the asymmetry of the Hausdorff distance in tree matching problems. For trees identified from the first laser acquisition (point set A) and the second acquisition (point set B), Hausdorff distances are first calculated from point set A to point set B, i.e. for each point (tree) in A, a closest point (tree) is found in B. We can then perform the same from B to A. The matched pairs are those that are the closest point to each other. The matching rate, defined as the number of matched trees divided by the total number of the trees in the plot/stand, represents the number of trees that could be automatically monitored. Figure 8 shows an example of tree-to-tree matching.

The best correspondence with the field measurements for individual tree growth was achieved with an R<sup>2</sup> value of 0.68 and an RMSE of 43 cm based on the difference between maximum laser hits. The results indicate that it is possible to measure the growth of an individual tree with multi-temporal laser surveys. The improved tree-to-tree matching method, based on minimizing the distances between treetops in the N-dimensional data space, was shown to be appropriate and necessary for growth evaluation based on individual trees.



**Figure 8.** Result of tree-to-tree matching using three variables for test plot 3. The matched trees are linked by line.

### **Paper V: Obtaining plotwise mean height and volume growth in boreal forests using multitemporal laser surveys and various change detection techniques**

In this paper, tree height and volume growth at plot level were determined using high-density multi-temporal laser scanner datasets acquired at different dates in a boreal forest. Similar techniques were developed as those in Paper IV and were applied to plot data. The objectives of the study were to assess the quality of laser-derived metrics for estimating forest height and volume growth at plot level and to compare several strategies and features used in the growth estimations. Regression models for growth prediction were developed based on the predictors derived from each method and assessed by cross-validation procedure.

The approaches developed for mean height and volume growth estimation at plot level were the individual tree top differencing method, digital surface differencing and analysis based on canopy height distribution. In the individual tree top differencing method, growth estimation was based on individual tree identification and a tree-to-tree matching algorithm. Individual trees were first detected by tree top finding, then tree-to-tree matching was performed to link the tree measured in different laser acquisitions and finally the mean difference of measured tree heights and the sum of estimated volume difference were taken for matched trees as the mean height and volume growth. The height for individual trees was determined from laser measurements by taking the maximum hit of the tree. Volume was calculated from existing volume equations using tree height and estimated DBH as independent variables.

In the digital surface differencing method, DSMs were first created for each plot from laser point clouds by taking the maximum laser hit fall in a grid area of 1 m x 1 m. The difference image was then created by subtracting the DSM of the earlier year from that of the later year. Since individual trees were not identified, growth in mean height was determined as: 1) a mean/median of the difference image for points that reflected from trees in both data sets; and 2) the difference in the mean/median of DSMs for

points that reflected from trees. A predictor for describing volume growth was determined as a function of mean height and estimated height growth.

The analysis based on canopy height distribution was based on the assumption that canopy height distribution in the vertical was influenced only by tree growth. Thus, changes in tree height will reflect changes in canopy height distribution. The mean height growth at the plot level was determined as the difference between different laser acquisitions in terms of the percentiles of canopy height distribution. A predictor for growth in volume was determined as a function of mean height and measured height growth.

The performance of the methods developed was evaluated with laser datasets acquired from all three laser surveys and field references, including 22 sample plots, in regression analyses. The reference growth at plot level, including tree height growth, DBH growth and volume growth, was estimated from field inventories conducted in 2001, 2004 and 2005 for 22 sample plots. The regression models were developed for mean height growth and volume growth using a single predictor derived from each method and selected predictors from all methods. The best-subset technique was used for predictor selection. The best results were obtained for mean height growth (an adjusted  $R^2$  value of 0.86 and a standard deviation of residual of 0.15 m) using the individual tree top differencing method. The corresponding values for volume growth were 0.58 and 8.39  $\text{m}^3\text{ha}^{-1}$  (35.7%) respectively, using DSM differencing. Combined use of the three techniques yielded a better result for volume growth (an adjusted  $R^2 = 0.75$ ) but did not improve the estimation for mean height growth (V: Table 2).

In general, tree height growth corresponded to field-measured growth of tree height better than volume growth did. All the techniques used have advantages and disadvantages. Individual tree based estimation was more demanding on laser data and computation than DSM differencing and canopy height distribution based methods for recognition of individual trees. However, estimates were more accurate with the first-mentioned than the latter. When there are cut/fallen trees in the test area, individual tree based and DSM differencing methods are more appropriate than the canopy height distribution based method because cut/fallen trees can change the canopy height distribution. In addition, seasonal changes in foliage of deciduous trees and undervegetation also have more impact on the canopy height distribution based method than the other two. The results indicated that it is possible to determine forest mean height and volume growth with acceptable accuracy using multi-temporal laser scanning.

## 6. DISCUSSION

In this thesis, the potential and applicability of ALS techniques for change detection were demonstrated and methods for detecting harvested trees and estimating the height and volume growth were developed. The results indicated that multi-temporal ALS is useful for forest change detection and growth estimation. The methods developed could be used for growth model development and in direct measurements of forest growth using strip-based sampling as part of large-area forest inventories, such as the national forest inventory. Also, the findings were supported by research done by other groups.

## 6.1 Previous Research

During the research process, a few studies were conducted concerning forest growth in height and volume using multi-temporal ALS data. In St-Onge and Vepakomma (2004), manually and automatically delineated tree crowns were used in deriving variables for detecting tree falls and estimating height growth using ALS data collected from different altitudes with two laser systems over a five-year period. The two surveys differed in many aspects, but most importantly in terms of density, which was 0.3 and 3 points/m<sup>2</sup> respectively for the first returns. They concluded that growth over five years could be measured with ALS data and that sensor-dependent effects were probably the most difficult to control in multi-temporal laser surveys for growth analysis purposes. Due to rapid technological developments, it is very likely that different sensors will be used in future, especially over long time intervals.

Næsset and Gobakken (2005) used various height metrics derived from canopy height distribution to establish forest growth by linear regression based on sample plots. ALS data were collected over a two-year period using the same system but different settings, resulting in a point density of 1.18 and 0.87 points/m<sup>2</sup>. They reported a prediction error for volume growth ranging from 50% to 100%, and their mean height growth predictions differed significantly from the field-estimated mean height growth using regression analysis with predictors derived from canopy height distribution. They concluded that over a two-year period, the prediction accuracy for plotwise and standwise change in mean tree height, basal area and volume was low when a point density of about 1 point/m<sup>2</sup> and canopy height distributions were used. They also reported that certain height measurements, such as maximum height, seemed less suitable than many other height metrics because they tend to be less stable.

Hirata (2005) extracted the individual tree growth of Japanese cedar using ALS data from 2001 and 2005 with a high point density (25-30 points/m<sup>2</sup>). The growth was estimated from the difference between two laser-derived DSMs. Since the forest consisted of trees with broad crowns, no tree-to-tree matching was performed to obtain the growth of trees. The relationship between sunny crown area and growth was also investigated. The general trend is that increment in DBH is greater as the sunny crown area increases.

Thies *et al.* (2006) developed a method for predicting the future development of forest stands by using laser-derived stand models and simulating sun eclipic. The method is based on a simple model to calculate the number of sun hits for the tree crown in a forest stand. The number of sun hits on the tree crown was estimated from ALS data. The results indicated a relationship between the diameter increment of trees and their crown exposure to sunlight.

A direct comparison between studies is impossible because they were conducted under different conditions and using data with different characteristics. However, the conclusions drawn from the studies are the same, that is laser data are able to estimate forest growth, even over a short period, but accuracy needs to be improved. This is possible if the factors that may affect the estimation are known.

## 6.2 Error Sources and Factors Influencing the Estimation

A precondition for change detection using remote sensing techniques is the

registration of multiple surveys relative either to each other or to a reference surface. Although the accuracy of laser measurements is very high, there are factors that may affect it, such as errors in GPS and INS, mounting errors, and fluctuation of the scanning mirror speed. Consequently, laser measurements at different times over the same area can display shifts in the X, Y, Z direction, especially if the ALS data were acquired using different systems. The accuracy of the registration can directly affect the accuracy of the growth estimation. A shift in Z could lead to a systematic error in the height growth estimates. A shift in X and Y could also cause an error in such estimates, especially in a hilly area. In general, the elevation of the point clouds can be calibrated using surfaces such as roads and lower branches on various parts of the DSM. Shifts in X and Y between the DSMs or point clouds could be calibrated using breaklines, such as the ridges of house roofs, if these are available in the images. It is important for the multi-temporal data sets to have been calibrated using the same techniques and same reference target in order to reduce any systematic shift between the datasets. To avoid any errors from DTM differences, the growth should be calculated from DSMs or point clouds instead of using tree height differences.

In individual tree based estimation, individual trees were normally identified by a tree top finding algorithm or by a segmentation procedure. The result of individual tree identification can greatly affect the accuracy of the growth estimation. In study II, the algorithm applied tended to merge two or more trees into one segment. In addition, the number of trees identified, their location and the shape of the tree segment can be quite different in different acquisitions, which could lead to other errors, i.e. mismatch of the tree from different acquisitions in tree-to-tree matching. Tree-to-tree matching accuracy is directly influenced both by individual tree top finding and by the match algorithm. The matching rate may vary significantly from stand to stand, depending on the stand structure. Inhomogeneous growth of trees within a plot results in poorer matching.

Cut and fallen trees and selecting thinning between different laser surveys can cause erroneous growth estimation if such cutting and thinning effects were not removed from the analysis, because they can significantly alter the canopy height distribution, resulting in misinterpretation of the growth. The problem can be avoided by conducting change detection to find cut/fallen trees and eliminate them from further analysis, or by conducting an analysis based on individual tree identification and tree-to-tree match, yielding no match for cut/fallen trees and thus eliminating them from further analysis.

It should be remembered that the results of forest growth estimation using methods developed do not correspond to the average growth of a stand but to the average growth of the trees visible with the laser scanner. Since the laser does not recognize all the smaller trees, it is obvious that growth estimates are weighted by the tallest trees. This impact may be minor, because in any stand most of the volumetric growth is concentrated on the dominant trees. Since the laser-based growth can be estimated as a function of tree height within the stand and within the given confidence limits, as demonstrated in Paper II, the effects of weighting by the tallest trees can be corrected if the height distribution of the trees is known.

Laser sampling density affects the laser-derived variables used to predict tree growth. With lower pulse densities, the probability of hitting the tree apex deteriorates, so growth estimates are affected by the varying sampling density. The laser sampling

density and recording geometry should therefore be kept stable across acquisitions. Even denser pulse density than was used in this study is now practical. There are systems allowing at least a 150 kHz sampling frequency. If low scanning angles, such as less than  $\pm 10$  degrees, and flying altitudes of 400 - 500 m are used, high sampling density can be achieved. Even though beam size has proved to have little effect on tree height determination (Næsset, 2004), it is expected that larger beam divergence is beneficial for growth estimation using tree apexes as long as the signal-to-noise ratio is sufficient.

In addition to the error sources mentioned above, there are other factors that may cause bias in the forest growth estimates. Weather conditions, such as strong wind, cause displacements of tree crowns. The same target can also be measured with two different measurement geometries, resulting in significant differences in the surface models and point clouds obtained. In change detection studies, it would be advantageous if the same flight planning could be applied in both acquisitions.

Trees typically grow at a rate between 5 cm and 1 m per year in the boreal forest zone. It is extremely difficult to estimate annual growth of the trees, given the error sources mentioned above. However, it is expected that estimation accuracy will improve when the time span between two laser acquisitions is increased to 5-10 years.

It should be noted that the variability in the stand structure of the test site was not very representative. For example, most sample plots used in the regression analysis were from mature forests; only one plot was located in a young stand. In addition, most of the plots were located in mixed stands and had a complex multi-layer structure making it very difficult to measure forest parameters using remote sensing techniques. A more accurate estimation of forest growth can be expected for a managed single layer forest. Furthermore, tree height and DBH were not measured at the same time as the laser acquisitions and we had to assume constant forest growth to derive the reference values. This may have introduced some errors into the reference data. In future studies, destructive cutting and boring should also be considered as potential reference growth measurement techniques since they seem to be the only reliable methods to obtain accurate information on past growth.

### **6.3 Methods and Further Development**

The method based on individual tree top differencing first needs to identify individual trees by tree top finding or segmentation. The accuracy of the identification can range from 40% to 91%, depending on the difficulty of the area and the characteristics of the data used (Hyypä *et al.*, 2001b; Persson, 2001; Leckie *et al.*, 2003; Tiede and Hoffmann, 2006). Errors in the identification and the way of linking the trees (segments) identified from different acquisitions can influence the growth estimates. For example, two trees were grouped as one segment in the first data and correctly identified as two segments in the second data, and when the tree was linked from two datasets, there were three choices: 1) one of the two segments in the second data was linked to one in the first data, 2) two segments in the second data were linked to the same segment in the first data, and 3) no link was made at all. The reasonable choice in our case is the first one. This kind of problem can be solved using our tree-to-tree matching algorithm. During the matching, errors in tree identification and therefore in links can be removed. In our experience, the quality of the matching is

more important than the quantity. In other words, more strict criteria should be used to get more accurate matching. The advantage of the individual tree matching technique is that it is able to discriminate between ingrowth and mortality/cut. To obtain gross growth, other techniques may be more feasible.

The problem with the DSM differencing method was the changes (noises) appearing in the difference image that were not related to the growth but were caused, for instance, by cut/fallen trees, crown coverage/shape changes, or penetration of the laser pulse through the canopy. The method is also very sensitive to the horizontal shifts between data sets. Due to the inaccuracy in GPS/INS and range measurements, possible strong wind blow and different viewing geometry, small shifts can be expected between different acquisitions, especially with different laser systems. The sampling density, filtering and rasterizing techniques applied also affect the results. It is possible to improve the estimates obtained by combining the DSM differencing and tree top differencing techniques: first, individual trees are found, then tree-to-tree matching is performed, and instead of taking the tree top difference value as the height growth, the difference in DSMs is considered. Thus each tree is separately matched to another laser data set in an optimal way. In this approach, problems arise when the same tree is measured from two different viewing angles.

The method based on the canopy height distribution is sensitive to changes in the distribution of the canopy heights with causes other than forest growth, such as thinning and cutting activities, natural disturbance, seasonal changes in the under-vegetation and the amount of foliage on deciduous trees. All these factors can cause changes in the canopy height distribution on which the canopy height distribution method is based. Therefore, the results should be interpreted with great caution when these effects exist, or the effects must be removed before growth is estimated if possible.

One important step in the individual tree based method is to find the individual trees. The methods for individual tree isolation using laser scanner data are still under development. The algorithm applied in this thesis tends to merge two or more trees into one segment, e.g. a smaller tree was grouped with a taller tree nearby. A more accurate algorithm is needed to improve the performance of individual tree delineation. One solution to the problem is to develop methods based on 3D point clouds instead of 2D CHM.

In the individual tree based method, tree height was determined by the maximum laser hits on the tree because the pulse density of ALS data is high. However, when the density decreases to 1 point/m<sup>2</sup>, for instance, using the maximum hit for tree height may not be appropriate because the likelihood of laser hits missing tree tops is greater. As a result, a new method needed to be developed. The use of tree models and reconstructions of tree shape for both acquisitions is one way to obtain accurate tree height and therefore better tree growth estimates. Another alternative is to use all the returns falling on crowns to assess the height growth. Similarly, use of a canopy surface model constructed from the CHM by removing the penetration of the laser pulses was expected to improve the assessment of growth.

Volume change in this thesis was mainly predicted from height and height change information. According to the latest knowledge in an inventory based on individual trees, it is expected that the use of tree-level laser height distribution characteristics, combined with variables of individual tree recognition (height, DBH), will improve the



prediction of individual tree stem volume. The use of improved individual tree based volume techniques with repeated laser measurements will also lead to an improvement in volume growth estimation. Other laser-derived metrics, such as variables describing the density of the stands and height variances, could be tested and included in the growth analysis.

One main drawback of the study is the lack of large number of the reference data. Because of this, evaluations of the developed methods were only based on limited materials, e.g. only pine was used in tree height growth analyses and 22 plots in mean tree height and volume growth analyses. However the methods developed do not impose any restricts on forest type or conditions (tree or stand characteristics) thus they can be adapted to any forested regions. Nevertheless the developed methods should be tested in different areas and for different types of forests. Given the complex of forest structure in the study area, the author only expects that accuracy will be improved when managed forest is considered.

Nowadays commercial ALS systems have the capability to record multiple returns and new-generation systems can even record the full waveform for each laser pulse. Such information is expected to improve the accuracy of growth estimates. The algorithms that work with multiple returns and waveform need to be developed.

The integration of ALS and aerial imagery has shown some advantages in retrieval of forest information (St-Onge *et al.*, 2004; Suarez *et al.*, 2005; Hyypä *et al.*, 2005b). Laser data provide accurate height information, which is lacking in single optical images, and also supporting information on the crown shape, depending on the pulse density used. Optical images in turn provide more details about spatial geometry and colour information that can be used to classify tree species and health so that tree growth can be analysed based on a stratification of tree species.

#### **6.4 Concept of Using the Change Detection Methods Developed**

The advantages of ALS for change detection include the high repeatability of tree height measurements with dense point clouds. The proposed methods might be used to replace a large number of permanent plots with ALS techniques. From that point of view, the strip sampling approach using high-density laser scanner data is a possible way of providing statistics on large areas.

A possible implementation scenario for measuring forest growth and other forest parameters with ALS techniques could be as follows:

- Large areas are measured with economical point densities (high altitudes, high scanning angles).
- A few cross strips are flown over at low altitudes (400-500 m), allowing point densities of 10-20 pulses per m<sup>2</sup>.
- Sample plots are placed on the cross strip areas.

The sample plots are then used to calibrate cross strip laser scanning, using techniques based on individual trees such as presented in Villikka *et al.* (forthcoming). A large area inventory is calculated using statistical methods, such as percentiles, and is calibrated using the field-calibrated individual tree based solutions. If these few strips are re-flown 5-10 years later, the growth can be determined. A breakdown between

ingrowth, mortality and cut can also be performed. With the help of digital aerial cameras and traditional change detection techniques, the major changes in a large forest area between two dates can be identified, and using repeated laser scanning and growth models the ingrowth can be generalized to the whole area.

## 7. SUMMARY

This thesis demonstrates the potential of high-density small-footprint ALS data for change detection in a boreal forest. Various methods were developed and tested for detecting forest changes caused by harvested trees and forest growth. Repeated, multi-temporal ALS data were acquired from three laser surveys between 1998 and 2003 using the TopoSys laser system. The shortest time period corresponds to one and half years of tree growth. A short summary of the statistical results obtained with the test data sets is listed below.

- Individual tree growth can be estimated with an accuracy of better than 0.5 m using multi-temporal ALS data.
- Out of 83 field-checked harvested or fallen trees, 61 trees were automatically detected. The difference in the number was mainly due to the segmentation procedure, which cannot distinguish smaller trees.
- The precision of the height growth estimated, based on field checking (3 plots) or statistical analysis, was typically about 10-15 cm at plot level and about 5 cm at stand level.
- The modified Hausdorff technique used for tree-to-tree matching is appropriate and effective for individual tree based growth analyses.
- An  $R^2$  value of about 0.75 and standard deviation of about 25% was obtained for plotwise volume growth based on a regression model with the volume growth predictors, derived from developed techniques, as independent variables.
- An  $R^2$  value of about 0.85 and standard deviation of 0.2 m were obtained for plotwise height growth based on the individual tree top differencing method alone.

There is clearly potential for the application of ALS in the automatic determination of tree height and growth information, even for a short period of time. The error and bias obtained for laser-derived individual tree height growth were compatible with those reported in an earlier study concerning field measurements of height growth. At plot level, estimated height growth corresponds better to the reference measurements than the estimated volume growth does. The results were extremely promising when several features were combined and reference growth data were used for calibration of the laser-based metrics. The results of harvested tree detection indicated that the method is very accurate in terms of determining the location and area of the change. If the number of trees harvested is required, small trees cannot be reliably detected.

In most cases, the individual tree based method was found to perform better in growth estimation than methods based on the difference in DSM and canopy height

distribution. However, it is worth noting that the pulse density of ALS data used in this study is high enough (10 points/m<sup>2</sup>) to solve individual trees although there may still be a problem with hitting the tree top. As the pulse density decreases, the other methods may perform better. The modified Hausdorff technique used for tree-to-tree matching is appropriate and effective for individual tree based growth analyses because it can utilize all the attributes associated with a tree as matching variables. In practice, attributes that do not change with time, such as location and species of the trees, should be the first choices. Attributes that change with time should be used with caution because this may result in poorer matching and cause mismatch. However, the use of such attributes could improve the match if they are compensated with a priori information on how the attributes have changed over time.

In order to avoid most errors in growth estimates, for instance, the same trees are measured from different points of the view, the author suggests that the planned flight trajectory information should be stored and repeated laser surveys are carried out with the same flight plan. This is especially important when the DSM differencing technique is used.

Judging by our results and experiences, some issues need to be further investigated. The factors that influence the accuracy of laser-derived DTM and tree height estimates, such as the pulse density, beam divergence and footprint size, could have effects on the growth estimates too. Using data from different sensors could also affect the results.

Monitoring growth patterns over a large area using field survey methods is a time-consuming and costly exercise. Thanks to higher pulse rates, a broader flight altitude range and lower costs, there is great potential that ALS in the near future will be used as a technique for collecting up-to-date information for continuous monitoring of forest resources and in the estimation of growth, typically carried out in national/large-area forest inventories. For this purpose, laser survey should be started as earlier as possible and repeated, for example in every 5-10 years. It is expected that the cost of large area forest inventories can be reduced and the quality of retrieved information improved by use of the proposed methods. At the same time, the need for accurate ground measurements could be reduced by combining ALS with field surveys.

The methods developed can be used to complement field measurements, to improve predictions from growth models and to develop new-generation forest growth models. When tree locations (competition between individual trees), their attributes (especially crown size, including length, area and even health), growth, and the way they cast shadows on each other are known, improvements in forest growth modelling can be expected. It is also expected that similar methods are feasible for reference measurements in studies analysing global forest changes and the carbon sink, in national forest inventories, and in describing the effects of global warming on forest growth and supporting the global decision-making process.

## 8. REFERENCES

- Ahern, F.J., 1991. A quantitative relationship between forest growth rates and Thematic Mapper reflectance measurements. *International Journal of Remote Sensing*, 12(3):387-400.
- Ahokas, E., Yu, X., Oksanen, J., Hyyppä, J., Kaartinen, H. and Hyyppä, H., 2005.

- Optimization of the scanning angle for countrywide laser scanning. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI(Part 3/W19), pp. 115-119.
- Aldred, A.H. and Bonnor, G.M., 1985. Application of airborne lasers to forest surveys. Information Report PI-X-51, Canadian Forestry Service, Petawawa national Forestry Institute, 62p.
- Anttila, P., 2002. Updating stand level inventory data applying growth models and visual interpretation of aerial photographs. *Silva Fennica*, 36(2): 549–560.
- Armenakis, C. and Savopol, F., 2004. Image processing and GIS tools for feature and change extraction. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 35, Part 4, pp. 611-616.
- Askne, J. and Santoro, M., 2005. Multitemporal repeat pass SAR interferometry of boreal forests. *IEEE Transactions on Geoscience and Remote Sensing*, 43(6): 1219-1228.
- Askne, J., Dammert, P., Ulander, L.M.H. and Smith, G., 1997. C-band repeat-pass interferometric SAR observations of forest. *IEEE Transactions on Geoscience and Remote Sensing*, 35(1):25-35.
- Assmann, E., 1970. The principles of forest yield study. (Oxford: Pergamon Press), 506 p.
- Axelsson, P., 1999. Processing of laser scanner data - algorithms and applications. *ISPRS Journal of Photogrammetry & Remote Sensing*, 54:138-147.
- Axelsson, P., 2000. DEM generation from laser scanner data using adaptive TIN models. In *International Archives of Photogrammetry and Remote Sensing*, Vol. 33, Part B4, pp. 110-117.
- Baltsavias, E.P., 1999. Airborne laser scanning: basic relations and formulas. *ISPRS Journal of Photogrammetry & Remote Sensing*, 54(2-3):199-214.
- Balzter, H., Baker, J.R., Hallikainen, M. and Tomppo, E., 2002. Retrieval of timber volume and snow water equivalent over a Finnish boreal forest from airborne polarimetric Synthetic Aperture Radar. *International Journal of Remote Sensing*, 23(16): 3185-3208.
- Balzter, H., Skinner, L., Luckman, A. and Brooke, R., 2003. Estimation of tree growth in a conifer plantation over 19 year from multi-satellite L-band SAR. *Remote Sensing of Environment*, 84:184-191.
- Batista, G.T., Shimabukuro, Y.E. and Lawrence, W.T., 1997. The long-term monitoring of vegetation cover in the Amazonian region of northern Brazil using NOAA-AVHRR data. *International Journal of Remote Sensing*, 18:3195-3210.
- Bauer, M.E., Burk, T.E., Ek, A.R., Coppin, P.R., Lime, S.D., Walsh, T.A., Walters, D.K., Bafort, W. and Heinzen, D.F., 1994. Satellite inventory of Minnesota forest resources. *Photogrammetric Engineering & Remote Sensing*, 60:287-298.
- Bazi, Y., Bruzzone, L. and Melgani, F., 2005. An unsupervised approach based on the generalized Gaussian model to automatic change detection in multitemporal SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 43(4): 874-887.
- Beauchemin, M., Thomson, K.P.B. and Edwards, G., 1998. On the Hausdorff distance used for the evaluation of segmentation results. *Canadian Journal of Remote Sensing*, 24(1):3-8.
- Bliss, J.C., Bonnicksen, T.M. and Mace, T.H., 1980. Computer-aided classification of forest cover types from small scale aerial photography. *Environmental*

- Management*, 4:499-510.
- Bovolo, F. and Bruzzone, L., 2005. A detail-preserving scale-driven approach to change detection in multitemporal SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 43(12): 2963-2972.
- Boyd, D.S. and Danson, F.M., 2005. Satellite remote sensing of forest resources: three decades of research development. *Progress in Physical Geography*, 29(1):1-26.
- Brandtberg, T. and Walter, F., 1998. Automated delineation of individual tree crowns in high spatial resolution aerial images by multi-scale analysis. *Machine Vision and Applications*, 11:64-73.
- Brandtberg, T. and Walter, F., 1999. An algorithm for delineation of individual tree crowns in high spatial resolution aerial images using curved edge segments at multiple scales. *Proc. International Forum on Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry*. (Hill, D.A.; Leckie, D.G., Editors). 10-12 Feb. 1998, Victoria, B.C., Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, pp. 41-54.
- Brandtberg, T., Warner, T.A., Landenberger, R.E. and McGraw, J.B., 2003. Detection and analysis of individual leaf-off tree crowns in small footprint, high sampling density lidar data from the eastern deciduous forest in North America. *Remote Sensing of Environment*, 85(3): 290-303.
- Bruzzone, L. and Prieto, D.F., 2002. An adaptive semiparametric and context-based approach to unsupervised change detection in multitemporal remote-sensing images. *IEEE Transactions on Image Processing*, 11(4): 452-466.
- Chapman, R.A., Heitzman, E. and Shelton, M.G., 2006. Long-term changes in forest structure and species composition of an upland oak forest in Arkansas. *Forest Ecology and Management*, 236:85-92.
- Chasmer, L., Hopkinson, C. and Treitz, P., 2006. Investigating laser pulse penetration through a conifer canopy by integrating airborne and terrestrial lidar. *Canadian Journal of Remote Sensing*, 32(2):116-125.
- Chubey, M.S., Franklin, S.E. and Wulder, M.A., 2006. Object-based analysis of Ikonos-2 imagery for extraction of forest inventory parameters. *Photogrammetric Engineering & Remote Sensing*, 72(4):383-394.
- Clark, M.L., Clark, D.B. and Robeerts, D.A., 2004. Small-footprint lidar estimation of sub-canopy elevation and tree height in a tropical rain forest landscape. *Remote sensing of Environment*, 91:68-89.
- Cloude, S.R. and Corr, D., 2003. Tree-height retrieval using single baseline polarimetric interferometry. *Proceedings of the Workshop on POLinSAR - Applications of SAR Polarimetry and Polarimetric Interferometry (ESA SP-529)*. 14-16 January 2003, Frascati, Italy (Editor: Lacoste, H). Published on CDROM.
- Cohen, W.B. and Spies, T.A., 1992. Estimating structural attributes of Douglas-fir/western hemlock forest stands from Landsat and SPOT imagery. *Remote Sensing of Environment*, 41:1-17.
- Colwell, J.E. and Hicks, D.R., 1985. NOAA satellite data: a useful tool for macro inventory. *Environmental Management*, 9(6):463-469.
- Coops, N.C. and Catling, P.C., 1997. Predicting the complexity of habitat in forests from airborne videography for wildlife management. *International Journal of Remote Sensing*, 18:2677-2686.
- Coops, N.C. and Waring, R.H., 2001. The use of multiscale remote sensing imagery to

- derive regional estimates of forest growth capacity using 3-PGS. *Remote Sensing of Environment*, 75:324-334.
- Coppin, P.R. and Bauer, M.E., 1994. Processing of multitemporal Landsat TM imagery to optimize extraction of forest cover change features. *IEEE Transactions on Geoscience and Remote Sensing*, 32(4): 918-927.
- Coppin, P., Jonckheere, I., Nackaerts, K. and Muys, B., 2004. Digital change detection methods in ecosystem monitoring: a review. *International Journal of Remote Sensing*, 25(9): 1565-1596.
- Cuomo, V., Lasaponara, R. and Tramutoli, V., 2001. Evaluation of a new satellite-based method for forest fire detection. *International Journal of Remote Sensing*, 22:1799-1826.
- De Wulf, R.R., Goossens, R.E., De Roover, B.P. and Borry, F.C., 1990. Extraction of forest stand parameters from panchromatic and multispectral SPOT-1 data. *International Journal of Remote Sensing*, 11:1571-1588.
- Donoghue, D.N.M., Watt, P.J., Cox, N.J., Dunford, R.W., Wilson, J., Stables, S. and Smith, S., 2004. An evaluation of the use of satellite data for monitoring early development of young Sitka spruce plantation forest growth. *Forestry*, 77(5):383-396.
- Dralle, K. and Rudemo, M., 1996. Stem number estimation by kernel smoothing of aerial photos. *Canadian Journal of Forest Research*, 26:1228-1236.
- Dubayah, R.O. and Drake, J.B., 2000. Lidar remote sensing for forestry. *Journal of Forestry*, 98(6):44-46.
- Eid, T. and Næsset, E., 1998. Determination of stand volume in practical forest inventories based on field measurements and photo-interpretation: The Norwegian experience. *Scandinavian Journal of Forest Research*, 13: 246–254.
- Elmqvist, M., Jungert, E., Lantz, F., Persson, Å. and Söderman, U., 2001. Terrain modelling and analysis using laser scanner data. estimation of laser radar data using active shape models. *International Archives of Photogrammetry and Remote Sensing*. Vol. 34-3/W4, pp. 219-227.
- Erikson, M., 2003. Segmentation of individual tree crowns in colour aerial photographs using region growing supported by fuzzy rules. *Canadian Journal of Forest Research*, 33:1557-1563.
- Evans, D.L., Roberts, S.D., McCombs, J.W. and Harrington, R.L., 2001. Detection of regularly spaced targets in small-footprint lidar data: Research issues for consideration. *Photogrammetric Engineering & Remote Sensing*, 67(10):1133-1136.
- Evans, D.L., Roberts, S.D. and Parker, R.C., 2006. Lidar – A new tool for forest measurements? *The Forestry Chronicle*, 82(2):211-218.
- Falkowski, M.J., Smith, A.M.S., Hudak, A.T., Gessler, P.E., Vierling, L.A. and Crookston, N.L., 2006. Automated estimation of individual conifer tree height and crown diameter via two-dimensional spatial wavelet analysis of lidar data. *Canadian Journal of Remote Sensing*, 32(2):153-161.
- Fensham, R.J. and Fairfax, R.J., 2002. Aerial photography for assessing vegetation change: a review of applications and the relevance of findings for Australian vegetation history. *Australian Journal of Botany*, 50(4): 415 – 429.
- Franco-Lopez, H., Ek, A.R. and Bauer, M.E., 2001. Estimation and mapping of forest density, volume and cover type using the k-nearest neighbors method. *Remote*

- Sensing of Environment*, 77: 251–274.
- Franklin, S.E. and Wulder, M.A., 2002. Remote sensing methods in medium spatial resolution satellite data land classification of large area. *Progress in Physical Geography*, 26:173-205.
- Fransson, J.E.S. and Israelsson, H., 1999. Estimation of stem volume in boreal forest using ERS-1 C- and JERS-1 L-band SAR data. *International Journal of Remote Sensing*, 20(1):123-137.
- Fransson, J.E.S., Walter, F. and Ulander, L.M.H., 2000. Estimation of forest parameters using CARABAS-II VHF SAR data. *IEEE Transactions on Geoscience and Remote Sensing*, 38(2): 720-727.
- Fransson, J.E.S., Smith, G., Walter, F., Gustavsson, A. and Ulander, L.M.H., 2004. Estimation of forest stem volume in sloping terrain using CARABAS-II VHF SAR. *Canadian Journal of Remote Sensing*, 30(4):651-660.
- Fujita, T., Itaya, A., Miura, M., Manabe, T. and Yamamoto, S., 2003. Canopy structure in a temperate old-growth evergreen forest analyzed by using aerial photographs. *Plant Ecology*, 168(1):23-29.
- Gaveau, D. and Hill, R., 2003. Quantifying canopy height underestimation by laser pulse penetration in small-footprint airborne laser scanning data. *Canadian Journal of Remote Sensing*, 29:650–657.
- Gill, S.J., Biging, G.S. and Murphy, E.C., 2000. Modeling conifer tree crown radius and estimating canopy cover. *Forest Ecology and Management*, 126(3):405-416.
- Gong, P., 1994. Integrated analysis of spatial data from multiple sources: an overview. *Canadian Journal of Remote Sensing*, 20(4):349-359.
- Gong, P., Sheng, Y. and Biging, G.S., 2002. 3D model-based tree measurement from high-resolution aerial imagery. *Photogrammetric Engineering & Remote Sensing*, 68(11):1203-1212.
- Gong, P. and Xu, B., 2003. Remote sensing of forests over time. Remote Sensing of Forest Environments (Edited by Wulder, M.A. and Franklin, S.E.), Kluwer Academic Publishers, pp 301-333.
- Gougeon, F.A., 1995. A crown-following approach to the automatic delineation of individual tree crowns in high spatial resolution aerial images. *Canadian Journal of Remote Sensing*, 21(3): 274-284.
- Gougeon, F. and Leckie, D., 2003. Forest information extraction from high spatial resolution images using an individual tree crown approach. Information report BC-X-396, Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 26 p.
- Gougeon, F.A. and Leckie, D.G., 2006. The individual tree crown approach applied to Ikonos images of a coniferous plantation area. *Photogrammetric Engineering & Remote Sensing*, 72(11):1287-1297.
- Haala, N. and Walter, V., 1999. Classification of urban environments using LIDAR and color aerial imagery. *International Archives for Photogrammetry and Remote Sensing XXXII (Part 7-4-3W6)*, pp 76– 82.
- Hall, D.B. and Bailey, R.L., 2001. Modeling and prediction of forest growth variables based on multilevel nonlinear mixed models. *Forest Science*, 47(3):311-321.
- Hall, S.A., Burke, I.C., Box, D.O., Kaufmann, M.R. and Stoker, J.M., 2005. Estimating stand structure using discrete-return lidar: an example from low density, fire prone ponderosa pine forests. *Forest Ecology and Management*, 208(1-3):189-209.

- Harding, D.J., Lefsky, M.A., Parke, G.G. and Blair, J.B., 2001. Laser altimeter canopy height profiles. Methods and validation for closed canopy, broadleaf forests. *Remote Sensing of Environment*, 76(3): 283-297.
- Hirata, Y., 2005. Relationship between crown and growth of individual tree derived from multi-temporal airborne laser scanner data. Presented at Silviscan 29 Sept.-1 Oct. 2005, VT, Blacksburg, Virginia.
- Hodgson, M.E., Jensen, J.R., Schmidt, L., Schill, S. and Davis, B., 2003. An evaluation of LIDAR- and IFSAR- derived digital elevation models in leaf-on conditions with USGS Level 1 and Level 2 DEMs. *Remote Sensing of Environment*, 84:295-308.
- Hoffmann, A. and Van der Vegt, J.W., 2001. New sensor systems and new classification methods: laser- and digital camera-data meet object-oriented strategies. *GeoBIT/GIS*, 6:18-23.
- Hofton, M.A., Rocchio, L., Blair, J.B. and Dubayah, R., 2002. Validation of vegetation canopy Lidar sub-canopy topography measurements for a dense tropical forest. *Journal of Geodynamics*, 34(3-4): 491-502.
- Hollaus, M., 2006. Large scale applications of airborne laser scanning for a complex mountainous environment. Doctoral Thesis, Vienna University of Technology, 111 p.
- Holmgren, J., 2003. Estimation of forest variables using airborne laser scanning. Doctoral Thesis, Department of Forest Resource Management and Geomatics, Swedish University of Agricultural Sciences, Umeå, 43 p.
- Holmgren, J., 2004. Prediction of tree height, basal area, and stem volume in forest stands using airborne laser scanning, *Scandinavian Journal of Forest Research*, 19(6):543-553.
- Holmgren, J., Joyce, S., Nilson, M. and Olsson, H., 2000. Estimating stem volume and basal area in forest compartments by combining satellite image data with field data. *Scandinavian Journal of Forest Research*, 15:103-111.
- Holmström, H., Nilsson, M. and Ståhl, G., 2001, Simultaneous estimations of forest parameters using aerial photograph interpreted data and the  $k$  nearest neighbour method. *Scandinavian Journal of Forest Research*, 16(1):67 – 78.
- Holmström, H., Kallur, H. and Ståhl, G., 2003. Cost-plus-loss analyses of forest inventory strategies based on kNN-assigned reference sample plot data. *Silva Fennica*, 37(3):381-398.
- Holopainen, M. and Jauhiainen, S., 1999. Detection of peatland vegetation types using digitized aerial photographs. *Canadian Journal of Remote Sensing*, 25:475-485.
- Holopainen, M. and Talvitie, M., 2004. Forest inventory by means of tree-wise 3D-measurements of laser scanning data and digital aerial photographs. *IAPRS XXXVI (8/W2)*, 6 p.
- Hopkinson, C., Chasmer, L., Young-Pow, C. and Treitz, P., 2004. Assessing forest metrics with a ground-based scanning LIDAR. *Canadian Journal of Forest Research*, 34:573-583.
- Hopkinson, C., Chasmer, L., Lim, K., Treitz, P. and Creed, I., 2006. Towards a universal lidar canopy height indicator. *Canadian Journal of Remote Sensing*, 32(2):139-152.
- Hudak, A.T. and Wessman, C.A., 1998. Textural analysis of historical aerial photography to characterize woody plant encroachment in south African savanna. *Remote Sensing of Environment*, 66(3):317-330.



- Hudak, A.T., Crookston, N.L., Evans, J.S., Falkowski, M.J., Smith, A.M.S., Gessler, P.E. and Morgan, P., 2006. Regression modeling and mapping of coniferous forest basal area and tree density from discrete-return lidar and multispectral satellite data. *Canadian Journal of Remote Sensing*, 32(2):126-138.
- Husch, B., Miller, C.I. and Beers, T.W., 1982. *Forest Mensuration*. 2<sup>nd</sup> Ed (New York: John Wiley & Sons).
- Hynynen, J., 1995. Modelling tree growth for managed stands. The Finnish Forest Research Institute. Research Papers 576. 59+76p.
- Hyppänen, H., 1999. Eriaikaiset ilmakuvat metsäkuvioiden muutosten tunnistamisessa. *Metsätieteen aikakauskirja*, 2: 155–166.
- Hyvönen, P. and Anttila, P., 2006. Change detection in boreal forests using bi-temporal aerial photographs. *Silva Fennica*, 40(2):303-314.
- Hyypä H. and Hyypä J., 1999. Comparing the accuracy of laser scanner with other optical remote sensing data sources for stand attributes retrieval. *The Photogrammetric Journal of Finland*, 16: 5-15.
- Hyypä, H., Yu, X., Hyypä, J., Kaartinen, H., Honkavaara, E. and Rönholm, P., 2005a. Factors affecting the quality of DTM generation in forested areas. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI(Part 3/W19) pp. 85-90.
- Hyypä, J., 1993. Development and feasibility of airborne ranging radar for forest assessment. PhD Thesis, Helsinki University of Technology, Laboratory of Space Technology, 112 p.
- Hyypä, J. and Inkinen, M., 1999. Detecting and estimating attributes for single trees using laser scanner. *The Photogrammetric Journal of Finland*, 16:27-42.
- Hyypä, J., Pulliainen, J., Hallikainen, M. and Saatsi, A., 1997. Radar-derived standwise forest inventory. *IEEE Transactions on Geoscience and Remote Sensing*, 35(2):392-404.
- Hyypä, J., Hyypä, 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*, 128:109-120.
- Hyypä, J., Pyysalo, U., Hyypä, H., Haggren, H. and Ruppert, G., 2000b. Accuracy of laser scanning for DTM generation in forested areas. *Proceedings of SPIE*. Vol. 4035:119-130.
- Hyypä, J., Kelle, O., Lehikoinen, M. and Inkinen, M., 2001a. A segmentation-based method to retrieve stem volume estimates from 3-D tree height models produced by laser scanners. *IEEE Transactions on Geoscience and Remote Sensing*, 39(5):969-975.
- Hyypä, J., Schardt, M., Haggrén, H., Koch, B., Lohr, U., Scherrer, H.U., Paananen, R., Luukkonen, H., Ziegler, M., Hyypä, H., Pyysalo, U., Friedländer, H., Uuttera, J., Wagner, S., Inkinen, M., Wimmer, A., Kukko, A., Ahokas, E. and Karjalainen, M., 2001b. HIGH-SCAN: The first European-wide attempt to derive single-tree information from laserscanner data. *The Photogrammetric Journal of Finland*, 17:58-68.
- Hyypä, J., Mielonen, T., Hyypä, H., Maltamo, M., Yu, X., Honkavaara, E., and Kaartinen, H., 2005b. Using individual tree crown approach for forest volume extraction with aerial images and laser point clouds. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI(Part

- 3/W19), pp. 144-149.
- Häme, T., 1988. Interpretation of forest changes from satellite scanner imagery. University of Helsinki, Department of Forest Mensuration and Management. Research Notes, 21, pp. 119-133.
- Häme, T., 1991. Spectral interpretation of changes in forest using satellite scanner images. *Acta Forestalia Fennica*, 222:1-111.
- Hökkä, H. and Groot, A., 1999. An individual-tree basal area growth model for black spruce in second-growth peatland stands. *Canadian Journal of Forest Research*, 29:621-629.
- Im, J. and Jensen, J.R., 2005. A change detection model based on neighbourhood correlation image analysis and decision tree classification. *Remote Sensing of Environment*, 99(3): 326-340.
- Israelsson, H., Ulander, L.M.H., Askne, J.I.H., Fransson, J.E.S., Fröling, P.O., Gustavsson, A. and Hellsten, H., 1997. Retrieval of forest stem volume using VHF SAR. *IEEE Transactions on Geoscience and Remote Sensing*, 35:36-40.
- Izzawati, Wallington, E.D. and Woodhouse, I.H., 2006. Forest height retrieval from commercial X-band SAR products. *IEEE Transactions on Geoscience and Remote Sensing*, 44(4): 863-870.
- Jauhainen, S., Holopainen, M. and Rasinmäki, A., 2007. Monitoring of peatland vegetation using digital aerial photographs. *Scandinavian Journal of Forest Research*, 22:168-177.
- Johnsson, K., 1994. Segment-based land-use classification from SPOT Satellite data. *Photogrammetric Engineering & Remote Sensing*, 60(1):47-53.
- Justice, C., Wilkie, D., Zhang, Q., Brunner, J. and Donoghue, C., 2001. Central African forests, carbon and climate change. *Climate Research*, 17: 229-246.
- Kadmon, R. and Harari-Kremer, R., 1999. Studying long-term vegetation dynamics using digital processing of historical aerial photographs. *Remote Sensing of Environment*, 68(2):164-176.
- Key, T., Warner, T.A., McGraw, J.B. and Fajvan, M.A., 2001. A comparison of multispectral and multitemporal information in high spatial resolution imagery for classification of individual tree species in a temperate hardwood forest. *Remote Sensing of Environment*, 75:100-112.
- Korhonen, L., Korhonen, K.T., Rautiainen, M. and Stenberg, P., 2006. Estimation of forest canopy cover: a comparison of field measurement techniques. *Silva Fennica*, 40(4): 577-588.
- Korpela, I., 2006. Geometrically accurate time series of archived aerial images and airborne lidar data in a forest environment. *Silva Fennica*, 40(1):109-126.
- Korpela, I. and Tokola, T., 2006. Potential of aerial image-based monoscopic and multiview single-tree forest inventory – a simulation approach. *Forest Science*, 53(3):136-147.
- Koskinen, J.T., Pulliainen, J.T., Hyyppä, J.M., Engdahl, M. and Hallikainen, M.T., 2001. The seasonal behavior of interferometric coherence in boreal forest. *IEEE Transactions on Geoscience and Remote Sensing*, 39(4):820-829.
- Kovats, M., 1997. A large-scale aerial photographic technique for measuring tree heights on long-term forest installations. *Photogrammetric Engineering & Remote Sensing*, 63(6):741-747.
- Kraus, K. and Pfeifer, N., 1998. Determination of terrain models in wooded areas with

- airborne laser scanner data. *ISPRS Journal of Photogrammetry & Remote Sensing*, 53:193-203.
- Kress, M.R., Graves, M.R. and Bourne, S.G., 1996. Loss of bottomland hardwood forests and forested wetlands in the Cache River Basin, Arkansas. *Wetlands*, 16(3):258-263.
- Kurvonen, L., Pulliainen, J. and Hallikainen, M., 1999. Retrieval of biomass in boreal forests from multitemporal ERS-1 and JERS-2 SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 37(1): 198-205.
- Larsen, M. and Rudemo, M., 1998. Optimizing templates for finding trees in aerial photographs. *Pattern Recognition Letters*, 19(12):1153-1162.
- Leckie, D.G., 1990. Advances in remote sensing technologies for forest surveys and management. *Canadian Journal of Forest Research*, 20(4): 464-483.
- Leckie, D., Gougeon, F., Hill, D., Quinn, R., Armstrong, L. and Shreenan, R., 2003. Combined high-density lidar and multispectral imagery for individual tree crown analysis. *Canadian Journal of Remote Sensing*, 29(5):633-649.
- Lefsky, M.A., Cohen, W.B., Acker, S.A., Parker, G.G., Spies, T.A. and Harding, D., 1999a. Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forests. *Remote Sensing of Environment*, 70:339-361.
- Lefsky, M.A., Harding, D., Cohen, W.B., Parker, G. and Shugart, H.H., 1999b. Surface lidar remote sensing of basal area and biomass in deciduous forests of Eastern Maryland, USA. *Remote Sensing of Environment*, 67:83-98.
- Lefsky, M.A., Cohen, W.B. and Spies, T.A., 2001. An evaluation of alternate remote sensing products for forest inventory, monitoring and mapping of Douglas fir forest in western Oregon. *Canadian Journal of Forest Research*, 31:78-87.
- Lefsky, M., Cohen, W., Parker, G. and Harding, D., 2002. Lidar remote sensing for ecosystem studies. *Bioscience*, 52:19-30.
- Lim, K., Treitz, P., Baldwin, K., Morrison, I. and Green, J., 2002. Lidar remote sensing of biophysical properties of northern tolerant hardwood forests. *Canadian Journal of Remote Sensing*, 29(5):658-678.
- Lim, K., Treitz, P., Wulder, M., St-Onge, B. and Flood, M., 2003. LIDAR remote sensing of forest structure. *Progress in Physical Geography*, 27(1): 88-106.
- Lowell, K., 1998. Evaluation of a moving-window algorithm for detecting individual tree stems from scanned aerial photographs in Victoria's eucalypt forests. *Australian Forestry*, 61:226-234.
- Lu, D., Mausel, P., Brondízio, E. and Moran, E., 2004. Change detection techniques. *International Journal of Remote Sensing*, 25(12): 2365-2401.
- Magnussen, S. and Boudewyn, P., 1998. Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators. *Canadian Journal of Forest Research*, 28: 1016-1031.
- Magnussen, S., Eggermont, P. and LaRiccia, V.N., 1999. Recovering tree heights from airborne laser scanner data. *Forest Science*, 45: 407-422.
- Maltamo, M., Mustonen, K., Hyypä, J., Pitkänen, J. and Yu, X., 2004. The accuracy of estimating individual tree variables with airborne laser scanning in boreal nature reserve. *Canadian Journal of Forest Research*, 34: 1791-1801.
- Matala, J., 2005. Impacts of climate change on forest growth: a modelling approach with application to management. Ph.D dissertation, Faculty of Forestry, University of Joensuu, Finland.

- Mayaux, P., Achard, F. and Malingreau, J.P., 1998. Global tropical forest area measurements derived from coarse resolution satellite imagery: a comparison with other approaches. *Environmental Conservation*, 25:37-52.
- Means, J. E., Acker, S.A., Fitt, B.J., Renslow, M., Emerson, L. and Hendrix, C.J., 2000. Predicting forest stand characteristics with airborne scanning lidar. *Photogrammetric Engineering & Remote Sensing*, 66(11):1367-1371.
- Meyer, P., Staenz, K. and Itten, K.I., 1996. Semi-automated procedures for tree species identification in high spatial resolution data from digitized colour infrared-aerial photography. *ISPRS Journal of Photogrammetry & Remote Sensing*, 51:5-16.
- Miller, O., Pikaz, A. and Averbuch, A., 2005. Objects based change detection in a pair of grey-level images. *Pattern Recognition*, 38(11): 1976-1992.
- Morsdorf, F., Meier, E., Allgöwer, B. and Nüesch, D., 2003. Clustering in airborne laser scanning raw data for segmentation of single trees. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol 34, part 3/W13, pp. 27-33.
- Morsdorf, F., Meier, E., Kötz, B., Itten, K.I., Bobbertin, M. and Allgöwer, B., 2004. LIDAR-based geometric reconstruction of boreal type forest stands at single tree level for forest and wildland fire management. *Remote Sensing of Environment*, 92:353-362.
- Murakami, H., Nakagawa, K. and Hasegawa, H., 1999. Change detection of buildings using an airborne laser scanner. *ISPRS Journal of Photogrammetry & Remote Sensing*, 54(2-3):148-152.
- Nelson, T., Boots, B., Wulder, M. and Feick, R., 2004. Predicting forest age classes from high spatial resolution remotely sensed imagery using voronoi polygon aggregation. *GeoInformatica*, 8(2):143:155.
- Nuutinen, T. and Kellomäki, S., 2001. A comparison of three modelling approaches for large-scale forest scenario analysis in Finland. *Silva Fennica*, 35(3):299-308.
- Nyysönen, A., 1955. On the estimation of the growing stock from aerial photographs. *Communicationes Instituti Forestalis Fenniae*, 46(1): 1-57.
- Næsset, E., 1997a. Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry & Remote Sensing*, 52:49-56.
- Næsset, E. 1997b. Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sensing of Environment*, 61: 246-253.
- Næsset, E., 2002a. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. *Remote Sensing of Environment*, 80:88-99.
- Næsset, E., 2002b. Determination of mean tree height of forest stands by digital photogrammetry. *Scandinavian Journal of Forest Research*, 17(5):446 – 459.
- Næsset, E., 2004. Effects of different flying altitudes on biophysical stand properties estimated from canopy height and density measured with a small-footprint airborne scanning laser. *Remote Sensing of Environment*, 91:243-255.
- Næsset, E. and Økland, T., 2002. Estimating tree height and tree crown properties using airborne scanning laser in a boreal nature reserve. *Remote Sensing of Environment*, 79:105-115.
- Næsset, E. and Gobakken, T., 2005. Estimating forest growth using canopy metrics derived from airborne laser scanner data. *Remote Sensing of Environment*, 96(3-4): 453-465.

- Næsset, E., Gobakken, T., Holmgren, J., Hyypä, H., Hyypä, J., Maltamo, M., Nilsson, M., Olsson, H., Persson, Å. and Söderman, U., 2004. Laser scanning of forest resources: the Nordic experience. *Scandinavian Journal of Forest Research*, 19(6):482-499.
- Packalén, P. and Maltamo, M., 2006. Predicting the plot volume by tree species using airborne laser scanning and aerial photographs. *Forest Science*, 52(6):611– 622.
- Packalén, P., Tokola, T., Saastamoinen, J. and Maltamo, M., 2006. Use of a super-resolution method in interpretation of forests from multiple NOAA/AVHRR images. *International Journal of Remote Sensing*, 27(24):5341-5357.
- Papathanassiou, K.P., Cloude, S.R., Reigber, A. and Boerner, W.M., 2000. Multi-baseline polarimetric SAR interferometry for vegetation parameters estimation. *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2000)*, Honolulu, Hawaii, Vol. VI, pp 2762-2764.
- Persson, Å., 2001. Extraction of individual trees using laser radar data. Chalmers University of Technology, Göteborg, Sweden, Department of Signals and Systems. 28 p.
- Persson, Å., Holmgren, J. and Söderman, U., 2002. Detecting and measuring individual trees using an airborne laser scanner. *Photogrammetric Engineering & Remote Sensing*, 68(9):925-932.
- Pinz, A.J., 1991. A computer vision system for the recognition of trees in aerial photographs. In J.C. Tilton (Ed.), *Multisource data integration in remote sensing. NASA Conference Publication*, 3099. pp. 111-124.
- Pitkänen, J., Maltamo, M., Hyypä, J. and Yu, X., 2004. Adaptive methods for individual tree detection on airborne laser based height model. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI(8/W2), pp. 187-191.
- Poage, N.J. and Tappeiner, J.C., 2002. Long-term patterns of diameter and basal area growth of old-growth Douglas-fir trees in western Oregon. *Canadian Journal of Forest Research*, 32:1232-1243.
- Pollock, R.J., 1994. A model-based approach to automatically locating individual tree crowns in high-resolution images of forest canopies. *Proc. of First International Airborne Remote Sensing Conference and Exhibition*. 11-15 September 1994, Strasbourg, France, III, pp. 357-369.
- Popescu, S., Wynne, R. and Nelson, R., 2003. Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. *Canadian Journal of Remote Sensing*, 29(5):564–577.
- Poso, S., 1983. Kuvioittaisen arvioimismenetelmän perusteita. Summary: Basic features of forest inventory by stands. *Silva Fennica*, 17(4): 313–349.
- Poso, S., Wang, G. and Tuominen, S., 1999. Weighting alternative estimates when using multi-source auxiliary data for forest inventory. *Silva Fennica*, 33(1):41-50.
- Pouliot, D.A., King, D.J., Bell, F.W. and Pitt, D.G., 2002. Automated tree crown detection and delineation in high-resolution digital camera imagery of coniferous forest regeneration. *Remote Sensing of Environment*, 82:105-115.
- Pulliainen, J.T., Heiska, K., Hyypä, J. and Hallikainen, M.T., 1994. Backscattering properties of boreal forests at the C-and X-band. *IEEE Transactions on Geoscience and Remote Sensing*, 32(5):1041-1050.
- Pussinen, A., 1992. Ilmakuvat ja Landsat TM –satelliittikuva välialueiden

- kuvioittaisessa arvioinnissa. M.Sc. in Forestry Thesis. University of Joensuu. 48 p.
- Päivinen, R., Nousiainen, M. and Korhonen, K., 1992. Puutunnusten mittaamisen luotettavuus. English summary: Accuracy of certain tree measurements. *Folia Forestalia* 787. 18 p
- Raber, G.T., Jensen, J.R., Schill, S.R. and Schuckman, K., 2002a. Creation of digital terrain models using an adaptive Lidar vegetation point removal process. *Photogrammetric Engineering & Remote Sensing*, 68(12):1307-1315.
- Raber, G.T., Hodgson, M.E., Jensen J.R., Tullis, J.A., Thompson, G., Davis, B. and Schuckman, K., 2002b. Comparison of LIDAR data collected leaf-on vs. leaf-off for the creation of digital elevation models. *Proceedings of the ASPRS 2002 Annual Convention*, 19-26 April, Washington, D.C. CD-ROM.
- Reigber, A., Neumann, M., Guillaso, S., Sauer, S. and Ferro-Famil, L., 2005. Evaluating PolInSAR parameter estimation using tomographic imaging results. *Proceedings of EURAD '05*. pp. 189-192.
- Reutebuch, S., McGaughey, R., Andersen, H. and Carson, W., 2003. Accuracy of a high-resolution lidar terrain model under a conifer forest canopy. *Canadian Journal of Remote Sensing*, 29:527-535.
- Rönholm, P., Hyypä, J., Hyypä, H., Haggrén, H., Yu, X., Pyysalo, U., Pöntinen, P. and Kaartinen, H., 2004. Calibration of laser-derived tree height estimates by means of photogrammetric techniques. *Scandinavian Journal of Forest Research*, 19(6):524-528.
- Saksa, T., Uuttera, J., Kolström, T., Lehtikoinen, M., Pekkarinen, A. and Sarvi, V., 2003. Clear-cut detection in boreal forest aided by remote sensing. *Scandinavian Journal of Forest Research*, 8(6):537-546.
- Santoro, M., Askne, J., Smith, G. and Fransson, J.E.S., 2002. Stem volume retrieval in boreal forest with ERS-1/2 interferometry. *Remote Sensing of Environment*, 81:19-35.
- Santoro, M., Askne, J. and Dammert, P.B.G., 2005. Tree height influence on ERS interferometric phase in boreal forest. *IEEE Transactions on Geoscience and Remote Sensing*, 43(2):207-217.
- Santos, J.R., Freitas, C.F., Aruajo, L.S., Dutra, L.V., Mura, J.C., Gama, F.F., Sola, L.S. and Sant'Anna, S.J.S., 2003. Airborne P-band SAR applied to the aboveground biomass studies in the Brazilian tropical rainforest. *Remote Sensing of Environment*, 87:482-493.
- Shackelford, A.K. and Davis, C.H., 2003. A combined fuzzy pixel-based and object-based approach for classification of high-resolution multispectral data over urban areas. *IEEE Transactions on Geoscience and Remote Sensing*, 41(10):2354-2363.
- Singh, A., 1989. Digital change detection techniques using remotely sensed data. *International Journal of Remote Sensing*, 10:989-1003.
- Sironen, S., Kangas, A., Maltoma, M. and Kangas, J., 2001. Estimating individual tree growth with the k-nearest neighbour and k-most similar neighbour methods. *Silva Fennica* 35(4):453-467.
- Sithole, G. and Vosselman, G., 2004. Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds. *ISPRS Journal of Photogrammetry & Remote Sensing*, 59:85-101.
- Smith, G. and Ulander, L.M.H., 2000. A model relating VHF-band backscatter to stem volume of coniferous boreal forest. *IEEE Transactions on Geoscience and Remote*

- Sensing*, 38(2/1):728-740.
- Steinle, E. and Bähr, H.-P., 2002. Detectability of urban changes from airborne laserscanning data. *Proceedings of the ISPRS Commission VII Symposium on Resource and Environmental Monitoring*, December 3-6, Hyderabad, India, ISSN 1682-1777.
- St-Onge, B.A. and Achaichia, N., 2001. Measuring forest canopy height using a combination of lidar and aerial photography data. *International Archives of Photogrammetry and Remote Sensing, Volume XXXIV-3/W4 Annapolis, MD, 22-24 Oct. 2001*, pp. 131-137.
- St-Onge, B. and Vepakomma, U., 2004. Assessing forest gap dynamics and growth using multitemporal laser scanner data. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI(8/W2), pp. 173-178.
- St-Onge, B., Jumelet, J., Cobelli, M. and Véga, C., 2004. Measuring individual tree height using a combination of stereo photogrammetry and lidar. *Canadian Journal of Forest Research*, 34(10): 2122-2130.
- Suarez, J.C., Ontiveros, C., Smith, S. and Snape, S., 2005. Use of airborne LiDAR and aerial photography in the estimation of individual tree heights in forestry. *Computers & Geosciences*, 31:253-262.
- Thies, M. and Spiecker, H., 2004. Evaluation and future prospects of terrestrial laser scanning for standardized forest inventories. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXVI, Part 8/W2* pp. 192-197.
- Thies, M., Pfeifer, N., Winterhalder, D. and Gorte, B.G.H., 2004. Three-dimensional reconstruction of stems for assessment of taper, sweep and lean based on laser scanning of standing tree. *Scandinavian Journal of Forest Research*, 19:571-581.
- Thies, M., Weinacker, H., Weinacker, R. and Pfeifer, N., 2006. Predicting forest growth processes by using laser scanner derived stand models and simulating sun ecliptic. *Workshop "3D Remote Sensing in Forestry"*, 14 -15 Feb. 2006, Vienna, CD-ROM.
- Thuy, Tuong Vu, Matsuoka, M. and Yamazaki, F., 2004. LIDAR-based change detection of buildings in urban areas. *Proc. International Geoscience and Remote Sensing Symposium*, IEEE, CD-ROM, 4 p.
- Tickle, P.K., Witte, C., Lee, A., Lucas, R.M., Jones, K. and Austin, J., 2001. Use of airborne scanning lidar and large scale photography within astrategic forest inventory and monitoring framework. *Proceedings of IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2001)*, Sydney, Australia. Vol 3, pp. 1000-1003.
- Tiede, D. and Hoffmann, C., 2006. Process oriented object-based algorithms for single tree detection using laser scanning. In *Workshop on 3D Remote Sensing in Forest*, 14-15 Feb. Vienna, Austria. CD-ROM.
- Tomppo, E., Nilsson, M., Rosengren, M., Aalto, P. and Kennedy, P., 2002. Simultaneous use of Landsat-TM and IRS-1C WiFS data in estimating large area tree stem volume and aboveground biomass. *Remote Sensing of Environment*, 82:156-171.
- TopoSys, 1996. Digital Elevation Models, Services and Products, 10 p.
- Trotter, C., Dymond, J. and Goulding, C., 1997. Estimation of timber volume in a coniferous plantation forests using Landsat TM. *International Journal of Remote*

- Sensing*, 18(10):2209-2223.
- Tuominen, S. and Haakana, M., 2005. Landsat TM imagery and high altitude aerial photographs in estimation of forest characteristics. *Silva Fennica*, 39(4):573-584.
- Tuominen, S. and Pekkarinen, A., 2005. Performance of different spectral and textural aerial photograph features in multi-source forest inventory. *Remote Sensing of Environment*, 94(2): 256-268.
- Utterä, J., Haara, A., Tokola, T. and Maltamo, M., 1998. Determination of the spatial distribution of trees from digital aerial photographs. *Forest Ecology and Management*, 110:275-282.
- Uzoh, F.C.C. and Oliver, W.W., 2006. Individual tree height increment model for managed even-aged stands of ponderosa pine throughout the western United States using linear mixed effects models. *Forest Ecology and Management*, 221:147-154.
- Varjo, J. and Mery, G., 2001. Forest change detection, *World forests, markets and policies* (M. Palo, J. Uusivuori, and G. Mery, editors), Kluwer Academic Publishers, Vol. 3, pp. 239-240.
- Villikka, M., Maltamo, M., Packalén, P., Vehmas, M. and Hyypä, J., Alternatives for predicting tree-level stem volume of Norway spruce using airborne laser scanner data. Submitted to *Scandinavian Journal of Forest Research*.
- Vosselman, G., 2000. Slope based filtering of laser altimetry data. *International Archives of Photogrammetry and Remote Sensing*, 33(B3/2), pp. 935-942.
- Vögtle, T. and Steinle, E., 2003. Detection and recognition of changes in building geometry derived from multitemporal laserscanning data. *IAPRS 34*.
- Walsh, S.J., 1980. Coniferous tree species mapping using Landsat data. *Remote Sensing of Environment*, 9:11-26.
- Walter, V., 2004. Object-based Evaluation of LIDAR and multispectral data for automatic change detection in GIS databases. *XXth ISPRS Congress*, 12-23 July 2004 Istanbul, Turkey (on CD-ROM).
- Watt, P.J., Donoghue, D.N.M. and Dunford, R.W., 2003. Forest parameter extraction using terrestrial laser scanning. *Proceeding of the ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests*, Umeå, Sweden, 2-4 September 2003, pp. 237-244.
- Wehr, A. and Lohr, U., 1999. Airborne laser scanning- an introduction and overview. *ISPRS Journal of Photogrammetry & Remote Sensing*, 54:68-82.
- Whiffen, H., Cieszewski, C., Borders, B., Lowe, R., Izlar, B., Zupko, M. and Cooke, W., 2000. Using 30-meter satellite data to estimate basal areas of intensively managed loblolly pine stands. PMRC Technical Report 2000, 67 p.
- Wilson, E.H. and Sader, S.A., 2002. Detection of forest harvest type using multiple dates of Landsat TM imagery. *Remote Sensing of Environment*, 80:385- 396.
- Wulder, M., 1998. Optical remote-sensing techniques for the assessment of forest inventory and biophysical parameters. *Progress in Physical Geography*, 22(4):449-476.
- Wulder, M., Niemann, K.O. and Goodenough, D., 2000. Local maximum filtering for the extraction of tree locations and basal area from high spatial resolution imagery. *Remote Sensing of Environment*, 73:103-114.
- Yu, X., Hyypä, J., Hyypä, H. and Maltamo, M., 2004. Effects of flight altitude on tree height estimation using airborne laser scanning. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXVI,



- Part 8/W2, 03-06 Oct. 2004, Freiburg, Germany, pp. 96-101.
- Yu, X., Hyypä, H., Kaartinen, H., Hyypä, J., Ahokas, E. and Kaasalainen, S., 2005. Applicability of first pulse derived digital terrain models for boreal forest studies. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI(Part 3/W19), pp. 97-102.
- Zimble, D.A., Evans, D.L., Carlson, G.C., Parker, R.C., Grado, S.C. and Gerard, P.D., 2003. Characterizing vertical forest structure using small-footprint airborne LiDAR. *Remote Sensing of Environment*, 87(2-3):171-182.