Estimation of Forest Variables using Airborne Laser Scanning

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Abstract

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Airborne laser scanning can provide three-dimensional measurements of the forest canopy with high efficiency and precision. There are presently a large number of airborne laser scanning instruments in operation. The aims of the studies reported in this thesis were, to develop and validate methods for estimation of forest variables using laser data, and to investigate the influence of laser system parameters on the estimates. All studies were carried out in hemi-boreal forest at a test area in southwestern Sweden (lat. 58°30'N, long. 13°40' E).

Forest variables were estimated using regression models. On plot level, the Root Mean Square Error (RMSE) for mean tree height estimations ranged between 6% and 11% of the average value for different datasets and methods. The RMSE for stem volume estimations ranged between 19% and 26% of the average value for different datasets and methods. On stand level (area 0.64 ha), the RMSE was 3% and 11% of the average value for mean tree height and stem volume estimations, respectively.

A simulation model was used to investigate the effect of different scanning angles on laser measurement of tree height and canopy closure. The effect of different scanning angles was different within different simulated forest types, *e.g.*, different tree species.

High resolution laser data were used for detection of individual trees. In total, 71% of the field measurements were detected representing 91% of the total stem volume. Height and crown diameter of the detected trees could be estimated with a RMSE of 0.63 m and 0.61 m, respectively. The magnitude of the height estimation errors was similar to what is usually achieved using field inventory. Using different laser footprint diameters (0.26 to 3.68 m) gave similar estimation accuracies. The tree species Norway spruce (*Picea abies* L. Karst.) and Scots pine (*Pinus sylvestris* L.) were discriminated at individual tree level with an accuracy of 95%.

The results in this thesis show that airborne laser scanners are useful as forest inventory tools. Forest variables can be estimated on tree level, plot level and stand level with similar accuracies as traditional field inventories.

Keywords: LIDAR, tree detection, species classification, scan angle, tree height, crown closure, laser measurement density

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Contents

Appendix

Papers I-V

The present thesis is based on the following papers, which will be referred to by their Roman numerals:

I. Holmgren, J., Nilsson, M. & Olsson, H. 2003. Estimation of tree height and stem volume on plots using airborne laser scanning. *Forest Science, 49(3)*: 419-428.

II. Holmgren, J., Nilsson, M. & Olsson, H. 2003. Simulating the effects of LIDAR scanning angle for estimation of mean tree height and canopy closure. Accepted for publication in *Canadian Journal of Remote Sensing.*

III. Holmgren, J. 2003. Prediction of tree height, basal area, and stem volume in forest stands using airborne laser scanning. Manuscript.

IV. Persson, Å, Holmgren, J. & Söderman, U. 2002. Detecting and measuring individual trees using an airborne laser scanner. *Photogrammetric Engineering & Remote Sensing, 68(9)*: 925-932.

V. Holmgren, J. & Persson, Å. 2003. Identifying species of individual trees using airborne laser scanner. Accepted for publication in *Remote Sensing of Environment.*

Introduction

Airborne laser scanning can provide three-dimensional (3D) measurements of both ground topography and forest canopy. The capability of laser beams to penetrate through vegetation makes it possible to measure ground elevation and canopy height with high precision even in dense forest (Baltsavias, 1999a). Three-dimensional coordinates of reflections from objects can be measured with accuracies of 0.1 to 0.3 m (Sterner, 1997).

Airborne laser scanners are, since a few years back, being commercially operated by a number of firms (Baltsavias, 1999b) and the number of installed commercial instruments is increasing. The instruments are operated at different altitudes above ground: low altitudes, resulting in high measurement density (several measurements per m^2) and high accuracy (0.1 to 0.3 m), and at high altitudes, resulting in lower measurement density and lower accuracy. Low altitude scanning is usually done for the purpose of measuring special objects, *e.g.*, infrastructure, and high altitude scanning is used for creating Digital Terrain Models (DTM) covering large areas. Some examples of geotechnical applications of airborne laser scanning are measuring roads, railway tracks, pipelines, waterway landscapes, electrical transmission lines, costal areas, urban areas, and water depths (bathymetry) (Wehr & Lohr, 1999).

There is currently a rapid technical development that will allow for operation at higher altitudes and with greater flight speed but with maintained high laser measurement density on ground (Flood, 2001). This development contributes to decreased operation cost, making it likely that airborne laser scanners will develop into cost efficient forest inventory tools. Further improvement of laser scanning products can be achieved by integration of the laser scanner with other sensors, such as optical imaging sensors (Flood, 2002). The present technical performance of laser scanning systems will be improved in the future and the technique will be used for more diversified applications (Ackermann, 1999). Because the hardware development is ahead of the development of application software there is a need to develop retrieval algorithms (Axelsson, 1999).

Although most laser scanning systems have been developed for purposes other than forest inventory, laser systems have proven to be more suitable for estimation of some important forest variables than several passive optical sensors (Hyyppä & Hyyppä, 1999; Lefsky, Cohen & Spies, 2001). Because most laser scanning systems not are optimized for forestry applications there is a need to investigate what system parameter settings are useful for forestry applications.

The process of forest information retrieval using an airborne laser scanning system together with field inventories can be described as a chain of activities (Figure 1). The laser scanner system produces three dimensional coordinates of reflection locations. The feature extraction (*e.g.*, using image analysis) gives laser variables from laser data. These laser variables are used together with measurements from a field inventory for statistical analysis (*e.g.*, using regression analysis). Finally, estimates of forest variables give information useful for forest management planning. There should also be a flow of information in the opposite direction. Ideally, the information needed in forest management planning systems or forest monitoring systems will decide what forest variables should be estimated, when they should be estimated, for what area they should be estimated, and with what accuracy they should be estimated. These needs should result in requirements concerning different laser variables derived, which in turn should result in different designs or parameter settings of the laser scanning system.

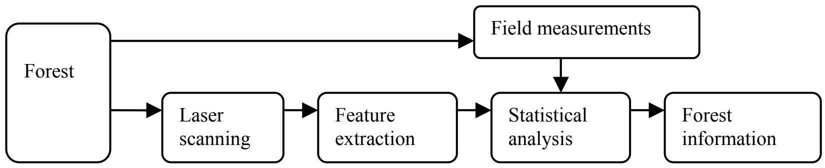

Figure 1. Retrieval of forest information, using an airborne laser scanner system together with field measurements.

Forest information

Monitoring

In Sweden, the National Forest Inventory (NFI) has been performed as a systematic field sample since 1923. The inventory provides information supporting decisions about timber and environmental policies on a national and regional level. Both the state of the forest and changes are assessed (Ranneby *et al.*, 1987). There is a need to also have information for smaller areas and to obtain better estimates of changes than is possible with the present design. Similar national inventories are also carried out in other countries.

Management planning

In forest management planning, inventories are performed to support decisions at different levels with different time horizons. Examples of such plans include strategic planning for long term timber supply at company level, tactical planning concerning allocation of forest operations in time and space, and operational planning of forest treatments, such as clear felling.

The inventory to support strategic planning among forest companies in Sweden is usually based on an objective field sample and during the last years has to a large extent been performed using the Forest Management Planning Package (FMPP) (Jonsson, Jacobsson & Kallur, 1993). The emphasis is on reducing potential sources of bias. Field plots are laid out in a regular pattern. Several variables are measured on these plots: tree variables measured on all trees, tree variables measured on a sample of trees, and site variables (Lindgren, 1984). Today, navigation satellite systems such as the Global Positioning System (GPS) allow for precise positioning of the field plots and it is therefore possible to efficiently link field measurements with remote sensing data.

For tactical planning, information about forest variables is needed for all geographical units in the forest. Random errors are usually larger than bias and emphasis is placed on reducing random errors (Jonsson, Jacobsson & Kallur, 1993). In Sweden, the geographical units are typically of the size 0.5 to 10 ha. They are delineated based on differences between forest stands, however economical and technical aspects also guide the delineation (Lindgren, 1984). A forest stand can be defined as a homogeneous parcel of land, all of the same stand type and larger than some defined minimum size. Forest stand types can be defined as forest land that has the same defined attributes chosen to classify the forest into homogeneous types (Davis & Johnson, 1987).

Remote sensing for monitoring

Optical satellite image data combined with ground reference data have been shown useful for county and nation wide forest mapping applications, especially for organizations needing overviews over large areas (Nilsson, 1997; Reese *et al.*, 2002; Tomppo *et al.*, 2002; Reese *et al.*, 2003). In Finland and Sweden, field data from the NFI have been used as reference data for estimation of stem volume using satellite spectral data. The accuracy for such estimates has been found to be poor on a pixel level, but the accuracy increases if the pixel-wise estimates are aggregated into larger areas (Fazakas, Nilsson & Olsson, 1999). Nilsson (1997) and Holmgren *et al.* (2000) have shown that that the estimation accuracy for stem volume of small areas increases when information of tree height is used in combination with satellite image data. Estimates of tree heights can be obtained using airborne laser measurements or stereo models of aerial photos. Satellite image data can also be used for mapping local changes in boreal forest caused by cuttings or damages (Olsson, 1994). Delineation of clear felled areas using difference between satellite images from different years is now being operationally implemented in Sweden on a national basis.

Remote sensing for management planning

The airplane, invented in 1903, was used as a camera platform as early as 1909 (Lillesand & Kiefer, 1994). Routine production of ortho-photos began during the 1950s (Kraus, 1993). The use of aerial photographs for forest inventory was at the same time being introduced widely in Sweden. Fifty years later, aerial photos in combination with field surveys is still the dominant method for stand mapping and forest variable assessment for forest management planning in Sweden. For small forest holdings interpretation with stereoscopes and measurements in field is generally used. For large forest holdings interpretation and measurements from more advanced photogrammetric instruments is used together with a supporting subjective field inventory (Åge, 1985).

Principles of laser scanning

For calculating the position of a reflection point (X, Y, Z) from an emitted laser beam, data from the following units are combined: positioning and orientation system, scanner, and Laser Range Finder (LRF) (Figure 2). The LRF measures the distance from the laser scanner aperture to the reflection surface. The beam direction relative the scanner (scan angle) must be known for each laser measurement. The position and orientation of the laser scanner system must be known for any time during the mission and is determined by combining a Differential Global Positioning System (DGPS) and an Inertial Navigation System (INS). Data from all units are time marked and stored in the control-, monitoring-, and recording-unit. The data from the different sources are linked using the time mark during the post-processing and X, Y, Z- coordinates are produced.

Different principles are used for the mechanism of the scanner, for example oscillating mirror, palmer scan, fibre scan, and rotating polygon (Wehr & Lohr, 1999). The laser measurements are distributed on the ground through the scan movement (rotation, oscillation, etc.) together with the forward motion of the aircraft. The frequency of the scan movements is here referred to as scan frequency.

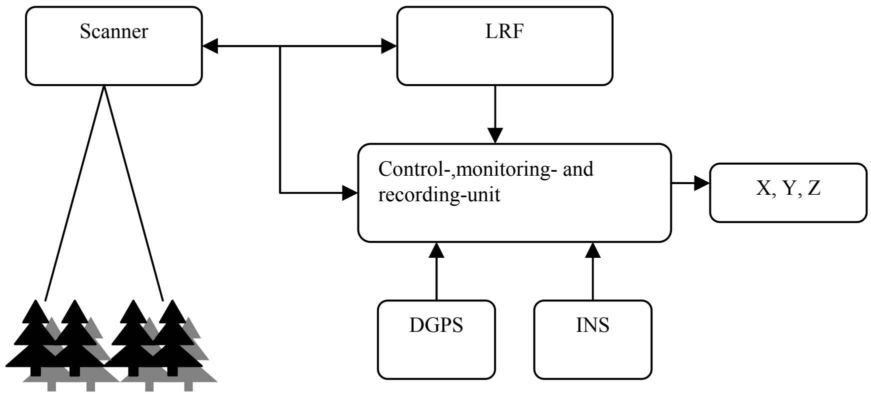

Figure 2. A typical laser scanner system producing three dimensional data (X, Y, Z coordinates). Based on Wehr & Lohr (1999).

The word laser is an acronym for *Light Amplification by Stimulated Emission of Radiation*. Using the physical properties of a laser, a powerful highly directional optical light beam can be generated. Lasers were therefore being used for very precise ranging shortly after being invented. As soon as lasers with high measurement rates were available, lasers could be used to obtain range images. Such systems are often called Laser Detection and Ranging (LADAR) or more generally Light Detection and Ranging (LIDAR) (Wehr & Lohr, 1999).

Two major principles are applied for range measurements: (1) the pulsed ranging principle, and (2) ranging by measuring the phase difference between the transmitted and the received signal. The phase difference method is applied with lasers that continuously emit light and are therefore called continuous wave lasers. In current airborne laser scanning systems, almost only pulsed lasers are used (Wehr & Lohr, 1999).

For pulsed lasers, the distance to the target is determined by the time-of-flight between the emitted and received pulse. The frequency by which pulses are emitted is here referred to as pulsing frequency (Hz). Ranging accuracy depends on the pulse-raise time but is also inversely proportional to the square root of the signal-to-noise ratio. The signal-to-noise ratio depends on many factors such as power of the received signal, input bandwidth, background radiation, and performance of signal detectors. Some requirements of an airborne laser scanner used for terrain mapping are enabling a high area coverage rate, having a short pulse and therefore a high range resolution and high range accuracy, and having enough pulse energy to enable a high flight altitude above ground. The systems should also be compact, efficient and reliable. Pulsed lasers are usually solid state lasers which produce high power output. A common type is the Nd: YAG laser, with pulse widths of 10-15 ns, 1.06 μm wavelength, and peak power up to several Megawatts (Wehr & Lohr, 1999).

The time of the received pulse is derived with a signal processing algorithm that might be system specific, for example, by using the time when an amplitude threshold has been reached. The performances of the algorithms are usually evaluated by distance measurements to a planar solid target. However, distance measurements to a non-solid surface, such as a tree canopy, is usually not evaluated. If different algorithms are being used for different systems, the distance measurements to a non-solid target might be system specific. The beam divergence and flight altitude above ground will determine the laser beam diameter on ground, which is commonly referred to as laser footprint diameter. The laser footprint diameter, power of the laser, and reflection properties of the target will also influence the distance measurements to the target.

Flight altitude and field of view determine the swath width on the ground. The swath width and flight speed give the coverage rate. Thus, the maximum suitable values of flight altitude above ground, field of view, and flight speed will determine the maximum coverage rate that is possible to achieve. The measurement rate will determine the measurement density for a specified coverage rate. Airborne laser scanners have therefore been developed during the last years with increased pulsing frequency to obtain a high measurement density with maintained high coverage rate. There are difficulties with using very high pulsing frequencies at high flying altitudes. This is because the high energy needed from high altitudes to obtain a good return is technically difficult to combine with a high pulsing frequency. The fact that a pulse cannot be emitted until the previous pulse has been received limits the possibility of combining very high pulsing frequencies with high altitudes. However, a new generation of laser scanners with increased measurement density is being developed. For these scanners, the returned light is not detected by a single detector but by an array of detectors. The systems are using Focal Plane Array (FPA) technique (Steinvall *et al*., 2001). For example, a laser beam with one meter footprint diameter illuminating the target combined with a 10×10 detector array would give a distance image for each emitted pulse with 0.1 m resolution. Thus, the measurement density can be increased without increasing the pulsing frequency.

The first LIDAR systems were operated in profiling mode and often used for bathymetry. From these early systems, small footprint terrestrial scanning systems were developed with higher pulsing frequency to meet the needs of geotechnical applications. These scanning laser systems usually have high horizontal resolution (≥ 0.3 m between laser measurements) and are discrete return systems that allow for one (*e.g*., first or last), two (*e.g*., first and last), or a few returns to be recorded for each emitted pulse. The time differences between the emitted pulse and each of the returned pulses are used together with sensor position and orientation data for calculation of each pulse reflection position. Some systems also record the reflectance of each pulse (Axelsson, 1999) that can be used for creating a monochromatic image of an area. Only data from a discrete return system have been used in this thesis.

There are also full-waveform digitizing LIDAR systems with large footprints (10-25 m diameter) that have been developed recently. These systems are designed as preparation for future satellite systems that will survey earth topography and vegetation height and cover. The large footprint will ensure that both the top of a tree canopy and the ground are captured in one pulse. The digitization of the waveform gives a vertical resolution of 0.5 to 3 m (Means, 2000). The Shuttle Laser Altimeter (SLA) and the Mars Observer Laser Altimeter (MOLA) have measured from space the topography of both Earth and Mars. The satellite remote sensing system Vegetation Canopy LIDAR (VCL) was planned to be launched (Blair, Rabine & Hofton, 1999) but the project is in danger of being cancelled. The VCL would consist of a five beam instrument in an 8 km circular configuration. Each beam would trace separate continuous ground tracks 2 km apart. Even if the VCL is never launched, several airborne systems have been developed as simulators for possible future satellite systems. One simulator is Scanning LIDAR Imager of Canopies by Echo Recovery (SLICER) and another is Laser Vegetation Imaging Sensor (LVIS) (Dubayah, Blair & Bufton, 1997). LVIS is designed to be operated at altitudes up to 10 km above ground (Blair, Rabine & Hofton, 1999).

Airborne laser scanning of forest

Analysis at stand and plot level

Tree height and canopy closure

The early profiling airborne LIDAR systems measured along a line in the flight direction. For a pulse passing vertically through the canopy, the first received energy peak (return) was from the top of the canopy, the following energy peaks were from different layers of the canopy, and the last peak was from the ground. The time differences between the first and last returns could be used to derive canopy heights. One curve was derived from a series of adjacent laser ground returns and another curve was derived from a series of adjacent canopy top returns. The area between the two curves, the cross sectional area, was compared with photogrammetric measurements. The full waveform of the returned energy was usually digitized by these early systems (Figure 3) and could be used for forest variable estimations.

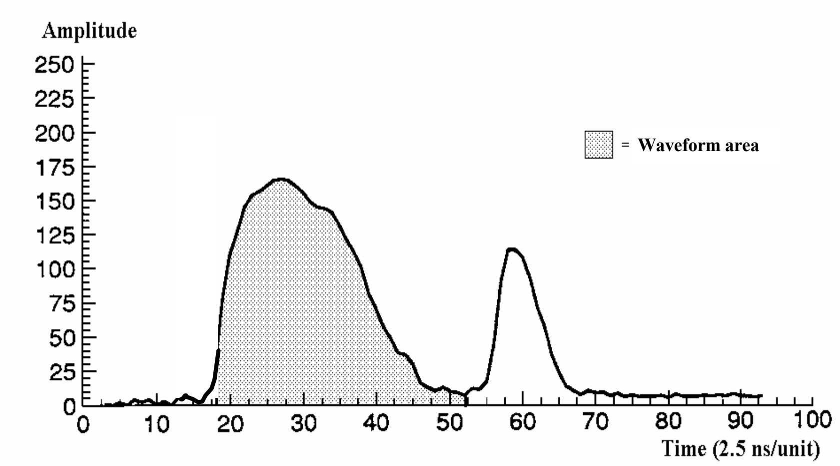

Figure 3. Waveform of relative reflectance (wavelength 532 nm). The shaded area represents the waveform area that was returned from the vegetation. From Nilsson (1996).

Profiling laser measurements were performed over Appalachian hardwood cover types (Nelson, Krabill & Maclean, 1984). One pulse with a wave length of 337 nm was emitted every 0.25 m along the ground track. The angular instantaneous field of view was 5 mrad and the flying altitude above ground was 150 to 450 m. Laser measured mean tree heights were comparable with photo interpreted mean tree heights. Furthermore, different laser variables were tested for estimating canopy closure using regression analysis. The amount of healthy crown was closely related to the number of pulses which hit the tree canopy and in which a ground signal could not be found in the wave form. An increase in cross sectional area was observed as canopy density increased.

Aldred & Bonnor (1985) experimented with individual laser returns from both softwood and hardwood forest using a near infrared laser. Crown cover density was estimated using a number of characteristics of the pulse returns: counts of the number of single returns, the maximum amplitudes of canopy and ground returns, the ratio of maximum power between peak pairs, and the area under the canopy portion of the waveform. Schreier *et al*. (1985) found that the relative reflectance and reflectance variability of a near-infrared laser were useful in discriminating between tree species and forest with different densities. Aldred & Bonnor (1985) used different algorithms to determine the time difference between the top canopy return peak and the ground return peak in order to estimate tree height. The peak-to-peak and leading-edge discriminators were found to be better than the trailing-edge discriminator. The best height estimate was achieved using 85% leading-edge threshold, but it was only slightly better than the peak-to-peak difference. Different time differences between the two peaks were also tested by Nilsson (1996). The scanning laser system, which emitted both green (532 nm) and infrared (1064 nm) light, measured a pine (*Pinus sylvestris* L.) stand in coastal

Sweden. The leading edge time difference resulted in the smallest underestimation of field measured tree height while the difference between centroids resulted in the lowest standard deviation. Although different time difference algorithms were tested, mean tree height (12 m) in the forest stand was underestimated by 2.1 m to 3.7 m. This was probably a result of laser beams that hit at the side of the conical tree crowns, rather than hitting close to the treetops.

Scanning airborne lasers primarily developed for geotechnical applications opened up new possibilities for laser remote sensing of forests. These systems have footprint sizes that are small and have high pulsing frequency in order to achieve high resolution data. However, only the reflection positions of one or a few returns can usually be derived (discrete return systems). Axelsson (1999) defines three steps in processing this kind of laser scanner data. First, unwanted measurements are removed. This step is referred to as filtering. For the purpose of measuring the ground, all non-ground measurements should be removed. Second, specific geometric structures, such as buildings or vegetation are found. This step is referred to as classification. Third, generalization of the classified objects is performed. This step is referred to as modelling. For forestry applications, the vertical distances between the laser measurements and the DTM (*i.e.*, the laser canopy heights) are calculated and then used in statistical models.

Næsset (1997a) used a laser scanner system that was operated so that only the last return of each emitted pulse was recorded. Estimation of basal-area-weighted mean tree height in forest stands was tested. Forest stands with a mean height ranging from 8 to 24 m were used for the analysis. The arithmetic mean of all laser height measurements in the canopy was found to underestimate the field measured mean height by 4.1 to 5.5 m. The underestimation was in accordance with results from earlier laser studies. However, grids of different sizes, for example 15×15 m^2, were placed over the forest map and only the maximum laser height value within a grid cell was retained. The mean of these grid cell values gave values that were close to the mean tree height with a bias of -0.4 m to 1.9 m. Standard deviations for the difference between the laser mean heights and the ground truth mean tree height were between 1.1 and 1.6 m.

Magnussen & Boudewyn (1998) introduced a geometrical model that successfully predicted the mean difference between the laser canopy heights and the mean tree height. The proportion of laser pulses returned from above a reference height was proportional to the fraction of leaf area above this reference height. Using the geometrical model confirmed earlier results which indicated that a grid approach where only the maximum laser height values within cells were retained could produce unbiased estimates of mean tree height. Magnussen, Eggermont & LaRiccia (1999) introduced two recovery models that could be used to obtain tree heights from laser height measurements. For the first model they assumed that the probability of a laser beam hitting a tree crown at or above a given reference height was proportional to the size of the horizontally projected crown area at this reference height. The second model was derived from the probability that a laser beam penetrated to a given canopy depth. The overall difference between canopy laser height and mean tree height was -3 m for 36 field plots. Using the recovery models, the bias was reduced to within 0.5 m of the field measured mean tree height.

Height percentiles of the distribution of canopy heights have been used as independent variables in regression models for estimation of mean tree height on field plots. Means *et al*. (2000) estimated mean tree height on forest plots (50×50 m^2) in Douglas-fir (*Pseudotsuga menziesii*) dominated forest in the western Cascades of Oregon. The tree height ranged from 7 to 52 m. The footprint diameter was about 0.6 m and the laser measurements were separated by 0.6 to 3.0 m. The height of each first return was calculated as the distance to the DTM below. Height percentiles from 0 to 100 were derived. A given height percentile was calculated as the height at a given percentage of laser returns. Stepwise regression analysis was used for selecting a regression model. The selected regression model produced a coefficient of determination (R^2) of 0.93. Typically one of the upper percentiles, the 90th height percentile, was included in the final model. Næsset & Okland (2002) used laser height percentiles for predicting mean tree height and average relative crown length on field plots. The mean tree height was predicted with a standard error of 1.5 m that was 7.6% of the average value and average relative crown length was estimated with a standard error of 6.3% to 7.1%.

A two-stage procedure was proposed and tested for prediction of mean tree height in forest stands using laser data (Næsset & Bjerknes, 2001). First, regression models were built at field plot level for estimation of forest variables based on laser derived variables. Second, the regression models were used for prediction of forest variables within predefined, *i.e*., photo-interpreted, forest stands. The predictions were then aggregated to stand level. Næsset & Bjerknes (2001) tested the procedure for prediction of mean height in young forest with tree heights less than 11.5 m and found the standard deviation of the difference between predicted and ground-truth mean height to be 0.56 m, or 8.4% of the average value. Næsset (2002) also used the procedure for older forest and found that the standard deviation of the difference between ground-truth and predicted mean tree height to be 0.61 to 1.17 m.

Stem volume and biomass

The possibility of estimating stem volume using variables measurable with photogrammetric methods was investigated as soon as aerial photos were used operationally in forestry. It was reported that in certain types of forests, stem diameter could be predicted with regression models using crown diameter (*e.g*., Minor, 1951; Hetherington, 1967; Jakobsons, 1970) or crown diameter together with tree height (*e.g*., Bonnor, 1964; Bonnor, 1968; Smith & Chiam, 1970). In 1982, Maclean & Martin (1984) used the cross sectional area derived from stereo models of vertical aerial photographs to estimate the natural logarithm of merchantable timber volume. Four years later, Maclean & Krabill (1986) estimated timber volume using cross sectional areas derived from laser profiles. The study area primarily contained loblolly pine (*Pinus tadea*) plantations and naturally occurring mixed hardwood and loblolly pine stands. They concluded, after studying residual plots, that the natural logarithm of data as input to the regression models was more appropriate than using un-transformed data. The selected model had cross sectional area as independent variable. Different cross sectional areas with exclusion of area below certain height levels were derived. After stratification based on tree species, the model produced an R^2 of 0.92.

Laser variables other than cross sectional area were also tested as independent variables in regression models. Nelson, Krabill & Tonelli (1988) estimated the natural logarithm of stem volume and biomass on 113 sample plots using a laser with green light (532 nm). Some laser variables used were cross sectional area, height value of largest laser canopy heights, average laser canopy height, laser canopy height standard deviation, and percent ground hits. The selected model explained between 53% and 56% of the variation noted in the ground measured biomass and volume on the plots. The laser derived variables used as a measure of forest canopy density were not very useful for prediction of stem volume and biomass.

Nilsson (1996) also used a laser with green light and did not found the ratio between number of canopy hits and total number of hits to be useful for estimation of stem volume. However, stem volume could be predicted with a regression model based on the product of the waveform area (Waveform area, Figure 3) and tree height derived from individual returns. The regression model produced an R^2 of 0.78.

The scanning airborne lasers developed for geotechnical applications have high pulse repetition frequency. Because of the scanning technique and the high pulsing frequency, laser measurements can be distributed over the forest with high density. It is therefore possible to not only derive laser variables related to the tree height distribution but also variables related to forest density. Thus, stem volume can efficiently be estimated within forest stands. Næsset (1997b) estimated stem volume at stand level within two separate test sites in Norway with a scanning laser using infrared light. The footprint diameter was about 13 to 16 cm and only the last returns of the laser pulses were recorded. The forest stand area ranged from 0.5 to 4.6 ha. The first test site was covered mainly by Scots pine with a volume range of 49 to 472 m^3 ha^{-1} and the second test site was covered mainly by Norway spruce with a volume range of 53 to 283 m^3 ha^{-1}. The mean value of the highest laser height value within squares of 15×15 m^2 as proposed by Næsset (1997a) was used as laser stand mean height. Two different measures of forest density were tested: (1) mean value of proportion canopy laser hits for squares within a forest stand, and (2) mean height value of all laser pulses within a forest stand. Two multiplicative models were used for estimation of stem volume. Both models included the laser stand mean height and each model included one of the two measures of forest density. Stem volume was predicted with a coefficient of variation of 43% for the first test site (R^2=0.46) and a coefficient of variation of 17% for the second test site (R^2=0.89).

Stem volume has been estimated at plot level using percentiles of the laser canopy height distribution combined with the ratio between number of vegetation measurements and total number of laser measurements. In the experiments in Douglas-fir dominated forest in the western Cascades of Oregon Means *et al.* (2000) estimated both stem volume and basal area. The stem volume ranged from

18 to 2051 m^3 ha^{-1} and consisted of shrub, young, mature, and old-growth forest. Laser variables related to forest density, canopy cover percentiles, were calculated as the proportion of first returns below a given percentage of total height. The canopy cover percentiles and height percentiles were used in stepwise regression analysis for selecting regression models. The predicted variables were transformed with the natural logarithm prior to estimation. The selected regression models produced an R^2 of 0.97 and 0.95 for stem volume and basal area, respectively.

The two-stage procedure with estimation on plot level followed by aggregation to stand level was also tested for stem volume predictions (Næsset, 2002). Field plots of 200 m^2 in size were used to build regression models predicting stem volume. The predictions at plot level were aggregated to forest stand level before validation. The forest stand area ranged from 0.7 to 11.7 ha. The field plots and forest stands were divided into three strata according to age class and site quality of the forest stands. Separate regression models were built for each stratum. The volume on the field plots ranged from 41 m^3 ha^{-1} to 640 m^3 ha^{-1}. The average footprint diameter was 0.2 m and average distance between laser measurements was 0.9 m. Stem volume and all independent variables consisting of height percentiles and canopy cover percentiles were transformed with the natural logarithm before used in the regression functions. Stepwise regression analysis was used for selecting a final model for prediction. Standard deviation on plot level for estimation of stem volume ranged from 29 to 62 m^3 ha^{-1}, 15% and 24% of the average value, and R^2 ranged from 0.80 to 0.93 for the different strata. The predictions at stand level gave standard deviations of stem volume estimations that ranged from 18.3 to 31.9 m^3 ha^{-1}, corresponding to a range between 11.4% and 14.2% of the average stem volume. The results imply that airborne laser scanning can be used operationally for prediction of forest variables at a stand level.

Analysis at single-tree level

Several image analysis methods have been developed for detection of individual trees in high resolution aerial images (*e.g.*, Gougeon, 1999; Erikson, 2001; Dralle & Rudemo, 1996, 1997; Brandtberg & Walter, 1998; Brandtberg, 1999; Pollock, 1996). Hyyppä & Inkinen (1999) demonstrated that high density laser measurements were useful for detection of individual trees as well as for deriving their characteristics such as height, location and crown diameter. The height of trees in the dominating story was obtained with a standard error of less than 1 m. Laser measured crown diameter and tree height were empirically related to stem diameter for estimation of basal area and stem volume and the estimations were aggregated to stand level. The mean tree height, basal area, and stem volume on stand level were estimated with standard errors of 2.3 m (13.6% of average value), 1.9 m^2 ha^{-1} (9.6% of average value), and 16.5 m^3 ha^{-1} (9.5% of average value), respectively. All accuracies were better than those normally obtained using traditional stand-wise field inventories. The segmentation method used for delineating individual tree crowns consisted of the steps pre-filtering, seed point extraction, and seeded region growing (Hyyppä *et al.*, 2001).

There are several studies that include tree detection using laser data that have been developed and tested in various forest types. An autonomous system for identification of individual trees using laser data was tested in coniferous forest in southern Sweden. The system was based on a scale-space technique approach with a differential geometry concept so that it was able to adapt itself to the locally dominating tree crown size (Brandtberg, 1999). Another method based on focal filtering was used in a stepped process for finding tree tops in plantations of Loblolly pine planted with 2.4×2.7 m^2 spacing (Young, Evans & Parker, 2000). There was a high correlation (>0.90) between the number of recorded trees in the field and the number of laser detected trees. Information about the tree crown size derived from the relationships between canopy height and crown diameter has also been used to guide tree detection. Local maximum filtering of laser data was applied to find treetops using a filter size that was determined by laser measured canopy height (Popescu, Wynne & Nelson, 2002).

Tree species classification can be done on an individual tree level using high resolution laser data. In Finland, a vector model of individual trees based on laser data has been developed. This vector model could be useful for tree species classification (Pyysalo & Hyyppä, 2002). Tree species classification using high resolution laser data was tested in an eastern deciduous forest in North America. Significant differences were found between the species oak (*Quercus spp*.), red maple (*Acer rubrum*), and yellow poplar (*Liriodendron tuliperifera*) (Brandtberg *et al*., 2003). Also crown length of individual trees has been estimated using laser data. Næsset & Okland (2002) estimated relative crown length of individual trees in southeastern Norway. They selected the coefficient of variation of laser heights from the canopy as the only variable for predicting relative crown length.

Influence of forest type on forest variable estimation

Estimation of mean tree height at plot level using the laser canopy height distribution might depend on tree species because different tree species usually have different crown shapes. This problem was investigated by Nelson (1997) who simulated laser measurements of tree crowns with different shapes. The average simulated height values increased as the shape varied from conical to spherical. The parabolic canopy shape appeared 8% to 10% taller, the elliptical canopy appeared 16% to 18% taller, and the spherical canopy appeared 23% to 25% taller than the conical canopy shape. Different canopy shapes might also influence biomass and volume estimations. Nelson (1997) found that regression estimates based on the assumption of a conical canopy shape applied on laser measurements of spherical shaped canopies resulted in an overestimation of basal area by 14% and an overestimation of biomass or volume by 20% or more on average.

Stem diameter, basal area, and stem volume can be estimated with laser data because the stem cross sectional area of individual trees can be empirically related to tree attributes that are more directly measurable by the laser, such as foliage area or foliage mass. It is very time consuming to measure foliage area even for a small field sample of trees. Therefore, field methods have been developed for estimation of foliage area by measuring sapwood basal area of individual trees. Whitehead (1978) predicted foliage area on plots and showed that foliage area should be related to sapwood basal area and not to total basal area. However, for trees of the same age and treatment, the ratio of sapwood basal area to total basal area is likely to be constant. Albrektson (1984) found a strong relationship between needle mass and sapwood basal area within forest stands and showed that the needle biomass per unit of sapwood basal area varied with mean annual ring width in the sapwood. Thus, the relationship between needle mass or foliage area and basal area of individual trees is probably dependent on factors such as forest treatment, site index, and age.

Several empirical studies using laser data have revealed that the relationships between laser derived variables and forest variables may vary for different forest types. Maclean & Krabill (1986) showed for a test area in Virginia that the canopy profile from a laser explained about 72% of the variation of the stem volume on plot level. After stratification for tree species, 92% of the volume variation could be explained. Research at a test area on the Cascade Range in Oregon has shown that the laser canopy height distribution might be different for different age classes, such as young stands, mature stands, and old-growth stands (Lefsky *et al*. 1999a). The time of the year that laser measurement of deciduous forest is performed may also be important. Rieger *et al*. (1999) used small footprints and found no off- terrain last returns from deciduous forest in the winter. On the other hand, coniferous trees showed similar patterns in both winter and summer.

Influence of system parameters on forest variable estimation

Early on, it was noted that implications of looking through the forest at different view angles when estimating forest variables would need to be investigated (Leckie, 1990). Næsset (1997a) estimated tree height in forest stands in Norway and found the coefficients for the off-nadir scan angle in the regression model to be not significant but argued that the exact effects of looking through the canopy at an angle should be quantified.

The laser measurement density available determines what methods are suitable for estimation of forest variables. The suitable estimation area unit must be determined, for example, forest stand, plot, or single tree. The results of tree detection depend on the forest structure, for example, the size of tree crowns and how close to each other the trees are located. Popescu, Wynne & Nelson (2000) simulated laser data using field measurements with mapped tree positions in order to develop algorithms for estimation of biomass based on tree detection. They used a method (Daley *et al*., 1998) developed for tree crown detection with high resolution remotely sensed imagery based on a local maximum filter. For coniferous stands, they observed a noticeable drop in R^2 for biomass estimation when using laser footprints and spacing between laser measurements larger than one meter. For deciduous stands, the best estimates of biomass were obtained when using laser footprints and spacing between the laser measurements of three meters.

The effect of using different footprint sizes for estimation of mean tree height has been investigated in different types of forests. Aldred & Bonnor (1985) found that the tree height was systematically underestimated by 1.5 m within softwood forest as a result of the tendency for pulse reflections to be somewhat below the conical treetops. A similar underestimation was found in hardwood forest. In the hardwood forest the error was found to be strongly related to beam width, with lower errors using wider beams. This difference due to beam size was less evident in softwood forest. The results indicated that a wider beam was optimal for height estimations in deciduous forest compared with the beam size optimal for softwood forest. Nilsson (1996) tested different footprint sizes with a diameter ranging between 0.75 and 3.0 m for tree height measurements in a pine stand. All footprint sizes were found to be useful for tree height estimation and different footprint sizes yielded the lowest errors for different laser acquisition dates.

The use of full wave-form digitizing large footprint laser systems could give new possibilities for estimating forest variables. These systems have recently been developed as simulators for planned satellite laser sensors but have already proven to be useful for estimation of forest variables in several types of forest including boreal, temperate and tropical forest (*e.g.*, Lefsky *et al*., 1999a, b; Means *et al*., 1999; Drake *et al*., 2002; Lefsky *et al*., 2002). Lasers with wide beams can also be used to measure ground elevation in dense tropical forest where smaller laser beams would rarely reach the ground. Ground elevation has been measured in tropical forest with a precision of 1 m (Hofton *et al*., 2002).

Objectives

A large number of airborne laser scanning instruments are presently operated with the potential of measuring forests. There are two general aims with this thesis: (1) to develop and validate methods that can convert laser data into useful forest information, and (2) to investigate what system parameter settings are suitable for forestry applications. Examples of system parameters are view angle, measurement density, and footprint size.

The specific objectives of the studies reported in papers I-V are listed below.

I. First, to develop and validate methods for estimation of mean tree height and stem volume at plot level. Second, to investigate the effect of view angle on laser variables related to mean tree height and canopy closure.

II. To investigate the effect of view angle on laser variables related to mean tree height and canopy closure using a simulation model.

III. First, to develop methods for prediction of mean tree height, basal area, and stem volume, and to validate these predictions at stand level. Second, to investigate the effect of laser measurement density on the estimation errors.

IV. First, to develop and validate methods for detection and measuring individual trees. Second, to investigate the effect of laser footprint diameter on the detection and estimation results.

V. To develop and validate methods for species classification of individual trees.

Material and Methods

Study area

The study area used for all studies in this thesis was located in hemi-boreal forest at the Remningstorp estate in southwestern Sweden (lat. 58°30'N, long. 13°40'E). The dominating tree species were Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.) and birch (*Betula spp*.). The area was essentially flat with variation in altitude ranging from 120 to 145 m above sea level.

Laser data

All laser data were produced using TopEye, an airborne laser system operated from a helicopter. The pulsed laser beam (wavelength 1064 nm) moves across the helicopter track controlled by the scanner and along track through the forward motion of the helicopter. The resulting pattern on the ground is thus z-shaped. The post-processing system calculates slant range, scanning angle, and position of the reflecting object (Sterner, 1997). The position of the reflecting object was derived from the first and last peak of the returned pulse. The intensity of each peak is also recorded.

Paper I

In a first mission, laser data were acquired on October 24, 1997. The beam divergence was 1 mrad, and the flight altitude was approximately 240 m above ground, giving a footprint diameter of 0.48 m on ground. The distance between scan lines in the centre of the flight line was approximately 0.8 m and the distance between laser points within a scan line was approximately 1.2 m. The approximate speed of the helicopter was 25 m s^{-1}. Flight lines were in a north-south direction and separated with a distance that resulted in a number of overlaps for the same forest area. There were therefore different sampling intensities depending on the number of flight lines with measurements covering a specific area.

Paper II-V

In a second mission, laser data were acquired on September 13, 2000. Laser measurements were made from five parallel flight lines in a north-south direction with a length of 2000 to 2500 m and a distance between the flight lines of 200 m. One dataset was produced with each of the four beam divergences. The beam divergences were 1, 2, 4, and 8 mrad, giving a footprint diameter of 0.26 m, 0.52 m, 1.04 m, and 2.08 m, respectively. The flight altitude above ground was approximately 130 m, the speed 16 m s^{-1}, the scan frequency 16.67 Hz, and the scan width ± 20 degrees. This gave a distance of 0.44 m between laser hits on ground within a scan line and 0.48 m between scan lines at nadir. Data acquisition was also performed at a flight altitude of 230 m and with a beam divergence of 8 mrad to produce measurements with a footprint diameter of 3.68 m. All other settings were the same as for the low flight altitude, giving a distance between the laser hits within a scan line of 0.79 m and a distance between scan lines of 0.48 m. From the high flight altitude, additional measurements were also made from five separate flight lines that were parallel to the main flight lines but shifted 50 m towards the east.

Inventory of circular plots

The circular field plots used in the studies had 10 m radius within which each tree with a diameter greater than 5 cm was callipered and tree species recorded. The age of the dominating trees and site index was also recorded. Height was measured for a sample of trees. The tree height measurements were used to calibrate functions for estimation of height and form height. The static functions used to derive height and form height had stem diameter as the most influential variable (Söderberg, 1992). Volume for all trees was estimated by multiplication of basal area and form height. For these functions Söderberg (1992) reports that estimates produced by the single-tree functions have a standard deviation of 11% for Scots pine, 13% for Norway spruce, and 15% for birch. The magnitude of these deviations decreases significantly at more aggregated levels (Lindgren, 1984). All inventories of circular field plots were performed using the Forest Management Planning Package (FMPP) (Jonsson, Jacobsson & Kallur, 1993).

Three types of inventories based on field plots were used: (1) field plots located systematically across the test area, (2) field plots within sampled forest stands, and (3) field plots within 80×80 m^2 squares. For the first inventory, field plots were placed using a grid with 100 m between plots in the north-south direction and 200 m between plots in the east-west direction. The location of the grid relative to the map was randomly selected. Data from this inventory were used in Paper I. For the second inventory, field plots were located using a grid within each sampled forest stand. The location of each grid relative to the map was randomly selected. The forest stands had been delineated using photo interpretation. Data from this inventory were used in Paper I and Paper III. For the third inventory, field plots were placed within 29 squares located in the centre of forest stands. Within each square, 16 field plots were placed on nodes of a regular grid with an inter-node distance of 20 m. Data from this inventory were used in Paper III.

Inventory of individual trees

Field data on an individual tree level were used in Paper II, Paper IV, and Paper V. Twelve rectangular field plots (20×50 m^2) were located along five parallel flight lines in the north-south direction. The forest consisted mainly of middle and old aged spruce and pine. The dominating species (> 80% of volume) was Norway spruce on six plots and Scots pine on six plots. Stem diameter for all trees (≥ 5 cm stem diameter 1.3 m above ground) within the plots was measured and the tree species recorded. The position of the centre of the tree stems was measured (1.3 m above ground) relative to two reference points in the nearest open area using a total station. The outline of the plot was determined in the same way as the position of the individual trees. Positions of the reference points were measured using kinematic GPS equipment. According to the specifications for the GPS equipment, accuracies of 5 cm were possible to achieve. For a random sample of trees (approximately 15 within each plot), the tree height, crown base height and crown diameter were measured. The heights were measured using an ultra sound distance measurement unit and an electronic angle decoder. The projected on ground crown diameter was measured in the direction of line of sight from the total station as specified by Jakobsons (1970). The position of the outermost part of the crown on both sides along the sightline was projected to the ground using a plumb line, and the distance between these two points on ground was then measured.

Analysis of laser data

Two separate approaches were used for estimation of forest variables. For the first approach, laser measurements were used to extract information about the spatial distribution of tree crowns and their heights on plots without detection of single trees. The methods used in this approach will be referred to as area based methods. For the second approach, laser measurements were used for detection of single trees. The methods used in this approach will be referred to as single-tree based methods. Tree detection can only be efficient if there are several laser measurements per tree crown. All estimations of stem volume (*vol*) at plot level were based on versions of the model

$$\ln(vol) = \beta_0 + \beta_1 \ln(h) + \beta_2 \ln(D) + \varepsilon \qquad (1)$$

where h is a laser measure of mean tree height, D is a laser measure of forest density, and ε is the error. This general model was used because it was assumed that stem volume could be modelled as a product of mean tree height and forest density. Simple linear regression models were used to relate laser variables to mean tree height.

Area based methods

Two types of area based methods will be described: (1) raster methods, and (2) height distribution methods. The raster methods use a 3D model of the canopy and are meaningful to use if the measurement density is high enough to give information about the horizontal spatial arrangement of tree crowns. For height distribution methods, the distribution of laser canopy heights is used together with laser derived variables related to forest density, for example, the ratio between number of laser canopy returns and total number of laser returns. These methods require laser measurement density high enough to give a sufficient number of laser measurements needed to obtain stable laser derived variables. Thus, the size of the estimation unit, field plot or forest stand, will determine the required measurement density.

Paper I

A raster method was tested using a raster with a cell size of one meter. The one meter resolution was chosen because it gave an expected frequency of at least one measurement per cell assuming that the laser measurements were evenly distributed over the field plot. The value of each raster cell was set to the value of the highest vegetation laser point within that raster cell. The canopy coverage area was defined as the area of the plot that had raster cell values more than 3 m from the ground level. For mean tree height estimation, the mean value of the raster height values on the plot was used as independent variable in a simple linear regression model. For stem volume estimation, the variables h and D (Equation 1) were set to mean height of raster height values and canopy coverage area on the plot, respectively. All mean tree heights estimated in this study were basal-area-weighted. The basal-area-weighted mean tree height is commonly referred to as Lorey's mean height.

Paper III

Height distribution methods were applied for prediction of basal-area-weighted mean tree height, basal area, and stem volume on plots. The estimations on plots were aggregated to stand level (80×80 m^2 squares). All mean tree heights estimated in this study were basal-area-weighted. Several laser height percentiles were tested for prediction of mean tree height. For estimation of stem volume a version of Equation (1) was used with h set to one of the height percentiles and D set to the percentage vegetation laser returns on the plot. Two other variables were also added to the model: (1) the relative standard deviation of laser canopy returns, and (2) a ratio based on the type of vegetation returns (single or multiple returns). Regression models were built using the field plots within all validation squares (80×80 m^2) except the one where forest variables were to be predicted. This was repeated until predictions were made for all validation squares. Regression models were also built using a separate training dataset of field plots. In order to investigate the effect of laser measurement density, the number of laser measurements was reduced before prediction.

Simulation of laser data

Paper II

The effects of view angle differences when estimating tree height and canopy closure were investigated by simulating laser measurements of forests. Four different forest types were simulated: (1) pine with constant tree height, (2) pine with tree height variation, (3) spruce with constant tree height, and (4) spruce with tree height variation. All trees in the different forest types had a crown diameter of 4 m. Trees in the pine forest had a crown length of 0.4 × tree height and trees in the spruce forest had a crown length of 0.8 × tree height. In the forests with constant tree height all trees had a height of 20 m. In the forests with tree height variation, the tree heights were rectangularly distributed (15 to 25 m). For each forest type, six datasets with stem densities 200, 400, 600, 800, 1000, and 1200 stems ha^{-1} were simulated. The trees were randomly placed. The individual trees were modelled as half ellipsoids. The geometric tree model was solid with no penetration of laser beams into the tree crown. The intersection between laser beam and closest object, half ellipsoid or ground, was calculated in order to derive the position for a laser reflection point. The simulation model was validated for nadir measurements by using field measured tree position, tree height, crown length, and crown diameter. Scanning angles were simulated between 0 and 30 degrees from nadir.

Single-tree based methods

Paper I

For single-tree-based analysis a continuous surface was created using kernel estimation. The kernel estimation was a weighted moving average of the laser height values (vertical distance from ground) for any raster cell. The effect of increasing the kernel bandwidth is to expand the region within which observed values influence the estimation. For very large bandwidth, the surface will appear flat and local features such as trees will be obscured. If the bandwidth is small, the surface will have high variation locally. Estimations were done only for locations and bandwidth where at least nine laser measurements could be included. The value was set to zero if there were not enough observations. The restriction of a minimum of nine laser points within the kernel was used in order to avoid local maximums of the surface caused by tree branches and not treetops. In order to choose a bandwidth for a plot, bandwidths were tested in the range 0.1 m to 4.0 m with 0.1 m intervals. The sum of squares over all laser measurement points of the distance between the interpolated surface and the measurement point was calculated for each bandwidth. The bandwidth giving the lowest mean sum of squares was chosen for estimation of the surface at that plot. A search was done for local maximums, which were assumed to correspond to treetops. A local maximum was defined as a grid cell having height values greater than any of the 8-connected grid cells. The number of trees was estimated as the number of local maximums in the interpolated surface. Tree heights were estimated for each of the individual trees or groups of trees corresponding to the maximums in the interpolated surface. Three different methods were tested for deriving height values at these locations: (1) using the value of the interpolated surface at the location of the maximum, (2) using the height value of the horizontally closest laser measurements to a maximum in the interpolated surface that had a greater height value than that in the surface maximum, (3) and using the height value that was derived by fitting a geometric tree model. The average of the derived height values were used as independent variables in simple linear regression models for estimation of mean tree height. Stem volume was estimated using a version of Equation (1) with h set to the average laser height value of individual trees and D set to the number of maximums of the continuous surface.

Paper IV

A method to create a Digital Canopy Model (DCM) of the tree crowns was used. First, an active contour surface (ACS) following the outer contour of the crowns was created and used to replace laser measurements not close to the contour. The ACS is based on the general theories of active contours (Cohen, 1991; Cohen & Cohen, 1993; Kass, Witkin & Terzopoulos, 1998). The ACS used was implemented in a routine developed for the purpose of model ground level elevation with laser scanner data (Elmqvist, 2000, 2002).

Elmqvist (2002) describes the model as a discrete two-dimensional surface in a three dimensional environment v[k] = (x (k), y (k), z (k)). The laser data are first resampled to a two dimensional height image **I** (x, y). The active shape model is represented by a height matrix **v** (x, y). The shape of the model is controlled by the energy function

$$E(v) = \sum \left(E_{\text{int}}\left(v[k]\right) + E_{im}\left(v[k]\right) + E_{ext}\left(v[k]\right) \right) \quad (2)$$

where E_{int} represents the internal energy of the model. It is a function of the first derivative of the model, giving the model elasticity, and is defined as

$$E_{\text{int}}\left(x, y\right) = C \sum_{m=x-1}^{x+1} \sum_{n=y-1}^{y+1} \left| \arctan \left(v\left(x, y\right) - v\left(m, n\right)\right) \right| \quad (3)$$

where C is the elasticity constant. E_{im} is a function of the distance between the measured surface and the model and is defined as

$$E_{im}\left(x, y\right) = -Ae^{-a(I(x,y)-v(x,y))^2} \quad (4)$$

where the constants *A* and *a* control the attraction strength and attraction length of the model. This function attracts the model with a strong force but on a short range, *i.e.* either the model is unaffected by **I** in a point or will attach to it. E_{ext} is an external force that is used to make the net start to interact with laser data.

Minimization of Equation (2) is done in an iterative process where E(v) decreases by updating the nodes of a net in small steps until a local minimum is reached. First, E_{int} and E_{im} are calculated for each node. E_{int} is always pointing along the Z-axis, up or down. E_{im} is given a sign making it pointing towards the measured laser point. When the forces have been calculated for every node the net is updated. The sign of the resulting force decides if the node in the net should move up or down. All forces in the net are calculated again and the net is then updated. This procedure is repeated until the net converges towards a solution with a tolerance that has been set. When the net has converged, the external force E_{ext} is turned off and iterations are continued until the net converges again. This routine was also used to derive a DTM. The values of *C*, *A*, and *a* were not changed prior to the validation in this study and were the same for all the analysis.

Local height variations, left after the ACS had been used to replace laser measurements below the outer contour of tree crowns were smoothed using a Gaussian filter. Three different Gaussian filter sizes were applied for creating three different images. The locations and heights of the trees were estimated by searching for a local height maxima in the smoothed images. Seeds were placed in every pixel more than 2 m from the ground and climbed in the direction having the largest slope. When a seed reached a position where all neighbour pixels had lower values, a local maximum was found. The crown area was estimated by grouping those pixels that climbed to the same maximum, and these pixels defined a segment. In order to calculate the crown diameter, the crown was assumed to be circular and the area of a segment was used. For each segment, the maximum laser height value above the ground surface (DTM) was chosen as the measure of tree height. The use of different Gaussian filter sizes resulted in different images with different segmentation. One problem was to choose the most appropriate scale in different parts of the image. For the same area there could be more than one segment in a finer scale but only one segment in a coarser scale. A parabolic surface was fitted to the laser elevation data in order to judge whether the additional segments were separate trees or only parts of a tree crown. To evaluate the results, each detected tree was automatically linked to the corresponding field tree. For each segment three different cases could occur: (1) no field trees were within the segment, (2) one field tree was within the segment, and (3) more than one field tree were within the segment. For case (1) the segment was judges as a segment that had no field tree. For case (2), the field tree was linked to the laser-detected tree. For case (3), the field tree was linked to the closest laser-detected tree. When the laser trees and the field trees had been linked with the rules above, each field tree that had not been linked was examined. For each of these trees, a search was done at a maximum distance of two pixels in all directions. If a segment was found that had not been linked and it was within the segment, the field tree was linked to this segment, otherwise the field tree was judged to be missed.

Tree species classification

Paper V

In a first step, a DCM was created and segmentation of individual tree crowns was performed as described in Paper IV. In a second step, tree species classification was performed based on the laser measurements within the segments. All laser points (x, y, z – coordinates) within each crown segment were considered to belong to the same tree.

The laser points were divided into three types determined by their location: ground points, within crown points, or DCM surface points according to their distance to the DTM or the DCM. The stem position was taken as the (x, y)-value of the highest laser point. The laser points were also divided into three types depending on the type of the return: (1) a single return with only one recorded amplitude peak, (2) the first return of a double return with two amplitude peaks, or (3) the second return of a double return with two amplitude peaks.

The variables used for tree species classification were based on proportion of laser returns from different types and measurements of height, geometry, and intensity. All variables were derived using only laser returns that were located above the crown base height. The crown base height was calculated using 0.5-m height layers. Each layer that contained less than 1% of the total number of non-ground laser points within the segment was set to zero and the others to one. To reduce the influence of laser points from low vegetation and neighbour trees, a one dimensional median filter (size 9) was first applied on the array of height layers. The crown base height was then defined as the distance from ground of the lowest laser data point above the highest 0-layer found. The relative crown base height was derived by dividing the crown base by the estimated tree height.

Several variables were derived based on the height (distance from ground) distribution of laser returns within the tree crown. Mean vertical distance between the first and last return of the double pulses was also derived. Proportion of single returns and the proportion of first returns were calculated. The proportion of vegetation points was defined as the number of returns that were located above the crown base height divided by the total number of returns from the segment. The proportion of DCM surface points was defined as the proportion of returns that were located near the DCM surface. The mean value and the variability of the returned intensity were also used for the classification. Classification was done both with a linear discriminant function and a quadratic discriminant function. The trees on one plot were classified using the trees on all other plots as training data. This was repeated until all trees on all plots had been classified.

Results and discussion

Tree height and stem volume at plot level (Paper I)

Mean tree height was estimated with a Root Mean Square Error (RMSE) ranging from 1.45 to 1.56 m for different but similar methods, corresponding to 10% and 11% of the average tree height. The systematic difference between laser measured and field measured mean tree height was lower for single-tree based methods compared with area based methods. One problem with area based tree height estimation methods is that laser height values from crown sides and from laser beams that have penetrated the crown surface will give a bias that could be different for different forest types. For example, earlier research has shown that mean height estimations with area based methods are sensitive to canopy shape (Nelson, 1997). Popescu, Wynne & Nelson (2002) and Schardt *et al*. (2002) detected individual trees in order to avoid the problem of including height measurements on the sides of tree crowns in the analysis. One problem is that any number of trees could remain undetected because the number of undetected trees depends on the forest structure.

Two regression models were used for estimation of stem volume. The first model, using laser derived tree height together with laser derived coverage area as independent variables, gave a RMSE of 37 m^3 ha^{-1}, corresponding to 22% of the average stem volume. The second model, using laser derived tree height together with laser derived stem number as independent variables, gave a RMSE of 43 m^3 ha^{-1}, corresponding to 26% of the average stem volume. This model would probably yield higher estimation accuracies if a laser dataset with higher measurement density was used.

It was found that different view angles did not influence the estimations of mean tree height. However, laser measured crown coverage area on plots was different for different view angles. The laser measured crown coverage area was lower for high view angles compared with low view angles. One reason for the low laser measured crown coverage area at high view angles compared to low view angles could be that trees shaded each other at high view angles. No height values could be assigned to the area of the shaded trees and the actual crown area was therefore underestimated. However, this shading effect could be reduced by measuring with overlapping laser swaths so that each location is viewed from two different flight lines.

Simulation of scanning angle effects (Paper II)

The simulations show that laser height percentiles and proportion of canopy returns changed more with an increased scanning angle for long crown species like spruce, compared to short crown species like pine. The upper height percentiles were less affected by scanning angle than were the lower height percentiles. The height percentiles changed more due to scanning angle in forests with low stem numbers compared with forest with high stem numbers. Also the proportion canopy returns changed more due to scanning angle in forests with low stem numbers and in forests with long tree crowns.

Although the simulation model used was simple (*i.e.*, with no penetration of laser beams into the crown) a high correlation (0.96) was found between simulated and real laser height percentiles for nadir measurements. The simulation model systematically overestimated the percentiles derived from field measurements by 2.25 m. One reason for this overestimation could be the restriction of no penetration of laser beams into the crowns. Because no off-nadir measurements with a small laser footprint diameter were available for the plots, the simulation model could not be validated for off-nadir measurements.

Correction for scanning angle effects when every location is viewed only from one location could be difficult because of the forest structure dependency. Information is needed about crown length and forest density (stems ha^{-1}).

Prediction of forest variables at stand level (Paper III)

For prediction of mean tree height at plots level, the RMSE was 1.07 m corresponding to 6% of the average value. When aggregating the predictions to 80×80 m^2 squares the RMSE was 0.59 m, corresponding to 3% of the average value (Figure 4).

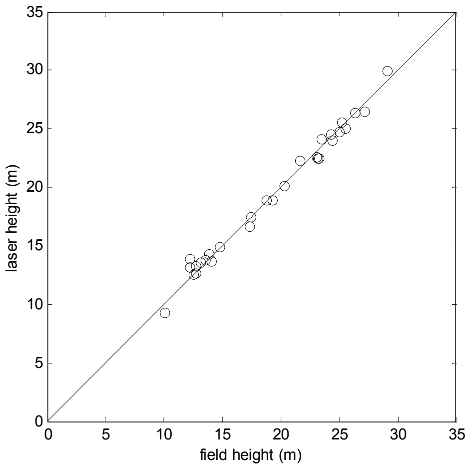

Figure 4. Estimated mean tree height plotted against field measured mean tree height for 29 squares each with the size 0.64 ha.

For prediction of basal area at plot level, the RMSE was 4.8 m^2 ha^{-1}, corresponding to 17% of the average value. When aggregating the predictions to 80×80 m^2 squares, the RMSE was 2.7 m^2 ha^{-1}, corresponding to 10% of the average value.

For prediction of stem volume at plot level, the RMSE was 55 m^3 ha^{-1}, corresponding to 20% of the average value. When aggregating the predictions to

80×80 m^2 squares, the RMSE was 31 $m^3\ ha^{-1}$, corresponding to 11% of the average value (Figure 5).

The results were obtained using cross validation using all field plots for training except those within the square where predictions were done. When using a separate training dataset for building the regression models, predictions were found to be less accurate.

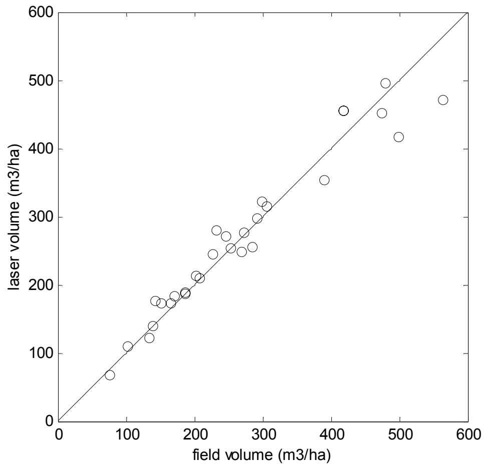

Figure 5. Estimated stem volume plotted against field measured stem volume for 29 forest stands each with the size 0.64 ha.

The estimation accuracies obtained for mean tree height, basal area, and stem volume at a stand level were similar to what was obtained by Næsset (2002) who predicted the same variables in similar forest types. One reason for the lower estimation accuracies reported in the current study when using a separate training dataset could be a result of different tree species proportions in the training dataset and the validation dataset. Næsset (2002) used different regression models for different strata, defined by age class and site index, which is correlated with the dominant coniferous trees in the region.

The RMSE for basal-area-weighted mean tree height, basal area, and stem volume estimations was similar for the different laser measurement densities (0.1 to 4.3 laser measurements per m^2). Nilsson (1994) found the height estimations to be reliable in a pine stand in coastal Sweden for distances between laser measurements up to 4.5 m.

Detecting and measuring individual trees (Paper IV)

In total, 71% of the field trees were detected and linked using laser scanner data, representing 91% of the total stem volume. There was a high correlation between laser measured and field measured tree height (Figure 6). Height and crown diameter of detected trees could be estimated with a RMSE of 0.63 m and 0.61 m, respectively. Stem diameter could be estimated with a RMSE of 3.8 cm using laser measured tree height and crown diameter as independent variables in a regression model. It was also found that similar detection and estimation results were obtained by using different laser footprint diameters (0.26 to 3.68 m). However, the smallest footprint size generated a better detection rate in dense forest compared with the larger footprint sizes.

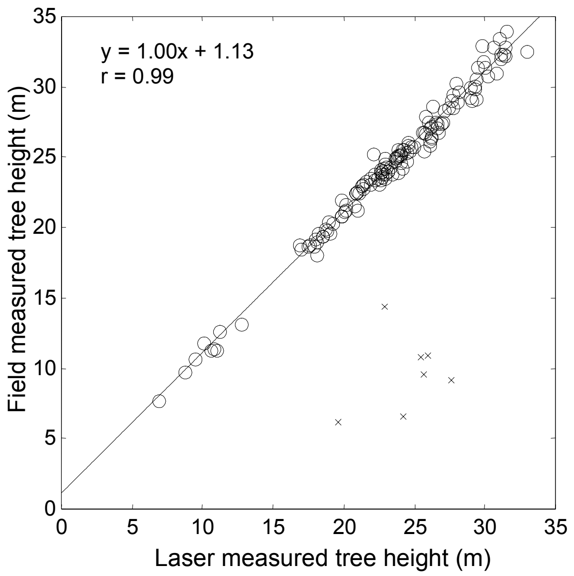

Figure 6. Field measured heights of sample trees plotted against laser measurements (135 trees). X-marks show trees that were incorrectly linked using automatic linking.

Results from algorithms that automatically or semi- automatically detect treetops in aerial images have usually been evaluated by comparing them with results from manual interpretation. It is difficult to compare results achieved using different methods because the studies have been performed at different test areas with different forest structure. For example, in our study the proportion of detected trees varied in our study from 41% to 96% probably as a result of different forest structure. The field plot with the lowest detection rate was found within a dense pine forest having low tree height and the field plots with highest detection rates were found within tall pine forest with relatively low tree height variation.

The accuracy of the tree height estimates (RMSE = 0.63 m) is comparable to the accuracy of the measurements achieved from the ground. The standard error for *Suunto* hypsometer measurements was in one study between 0.4 m and 0.8 m (Lindgren, 1984). If one assumes that measurements with the electronic hypsometer used in this study had the same standard error, a significant portion of the RMSE could be caused by error in the field data. The errors for hypsometers are also usually larger for tall trees than for short trees.

Hyyppä *et al.* (2000) validated tree heights from a high resolution airborne laser scanner system in Finland. They found the RMSE for measurements of 89 trees to be 0.98 m, similar to what was observed in this study, but the bias was much lower (0.14 m). The lower bias in the Finnish study could be caused by the extremely high resolution (24 measurements m^{-2}), making it more likely that the uppermost part of the treetop was hit.

All beam divergences tested for detection and height measurements of individual trees were useful. The small influence of footprint size on height estimates is in agreement with earlier studies. In the investigations by Aldred & Bonnor (1985), and in the study by Nilsson (1996), small differences were found in height estimation errors for softwood forest using different beam divergences.

Identifying species of individual trees (Paper V)

It was possible to discriminate between Scots pine and Norway spruce of individual trees using laser data. The overall classification accuracy was 95%. The pine trees were more often misclassified than were the spruce trees. The classification results were similar for the two tested discriminant functions. There was a high correlation (r = 0.84) between field measured crown base height and laser measured crown base height.

The large variation that naturally exists between individual trees, even within trees of the same species, might explain much of the misclassification. The spruce trees are usually more conical than the pine trees. However, pine trees can have different shapes depending on age, usually with more conical crowns for younger pine trees. The shape of the crowns could also be influenced by competition from neighbour trees making the shape of pine trees more conical and therefore similar to a spruce tree. The spruce trees were sometimes placed next to the stem of a pine tree with their treetops close to the pine crowns. The pine crowns could therefore have been mixed with spruce trees and in that way influenced the classification result.

The variables used for the classification can be divided into two groups. The first group includes variables that measure the shape of the tree. These variables can be assumed to be rather stable and not too dependent on the system, system settings, or seasonal difference of the trees. The second group includes variables that do not measure the shape of the trees, for example, variables derived from the returned intensity. These variables probably depend to a large degree on the system, system settings, and seasonal difference of the trees.

Conclusions

Although the material in the thesis is limited to using data from only one test area, the conclusion is that the estimation accuracy shows that airborne laser scanning is useful for forest inventory. There are several factors that should be taken into concern when using an airborne laser scanner for forest inventory.

For estimations of forest variables using laser data at plot level, the estimations could be influenced by scanning angle. Simulations show that the effect of different view angles on measurements of tree height and canopy closure will be different for different crown length and forest density (stems ha^{-1}). Without knowing crown length and forest density, it might therefore be difficult to correct for the effect of different view angles. Because of problems with high view angles one should therefore be restrictive and if possible use small view angles, for examples up to 10 degrees from nadir. The methods tested in this study to estimate mean tree height, basal area, and stem volume using the height distribution of laser measurements were not sensitive to decreasing laser measurement density. Almost the same prediction accuracies were achieved with laser measurements separated by several meters as with several laser measurements per m^2. The results also indicated that mean tree height, basal area, and stem volume can be estimated even in small forest stands (0.64 ha) yielding similar accuracies as those achieved with traditional field inventories. However, the relationships between laser variables and forest variables could be forest type dependent.

Using high resolution airborne laser scanner data, individual trees can be detected and forest variables on a tree level can be derived. The probability that a specific tree is detected depends on its distance to the closest other tree and the relative height of this specific tree. Because the errors of the tree height estimations are similar to what is achieved with traditional field measurement of individual trees, expensive field measurements could be reduced. However, the laser measurements of individual trees must be combined with a field sample in order to build regression models. Because of the geographically limited material in this study no conclusions can be made about an appropriate geographical allocation of the field sample. Stem diameter of the detected trees could be estimated using laser measured tree height and laser measured crown diameter. However, we do not know how well stem diameter can be estimated for a larger area with different site conditions. The smallest laser beam diameter (0.26 m) was more effective for tree detection compared with other laser beam diameters when there was a short distance between trees. However, measurements of tree height and crown diameter were not influenced much by different laser footprints. Promising results were achieved for tree species classification of pine and spruce on an individual tree level. The segmentation of individual tree crowns allows for extraction of variables that can be used for discriminating between tree species. Several laser variables, derived from both the shape of the trees and from the returned intensity, were useful for tree species classification. Some of these variables could be site specific and thus require a local training dataset.

Applications

Airborne laser scanning for monitoring

Because detailed measurements can be obtained from airborne laser scanning, local changes caused by thinning or forest damages would probably be possible to estimate with high accuracy. Strip sampling with repeated laser measurements with a few years interval together with field measurements in a multiphase sampling design might be a cost-efficient way for large area sampling inventories (national forest inventories) to derive estimations of changes. Since only measurements within strips are needed these methods would not be very sensitive to high costs per area unit. High resolution laser data could also be used for collecting data of special ecological interest, for example, topography and forest structure close to rivers.

Airborne laser scanning for management planning

An objective field sample of DGPS positioned plots and a complete coverage of laser measurements could be used to predict forest variables on plot level. These predictions could then be used to produce a raster data base covering all forest land. The raster based predictions could be aggregated to predefined forest stands represented by polygons on a forest map. The subjective field inventory methods currently used in Sweden for forest variable estimation at stand level have a standard error of 15% to 25% for stem volume and about 10% for tree height estimations (Ståhl, 1992). The results in this thesis and other studies show that it is possible to estimate these forest variables at a stand level with similar or higher accuracies using airborne laser scanning combined with a field sample. Raster predictions might also be used directly in forest management planning systems. For example, raster models have been considered in Sweden for defining optimal treatment areas (*e.g.*, Holmgren & Thuresson, 1997; Lu & Eriksson, 2000; Lind, 2000; Öhman, 2001). Tree detection based on high density laser measurements can be used where detailed information is needed, for example, to support operational planning of forest treatments such as clear felling.

Future research

Estimation of forest variables using airborne laser scanning has in this thesis been performed both at plot level (area based methods) and by detection of individual trees (single-tree based methods). Thanks to technical developments, airborne laser scanners will in the future provide high resolution 3D information of the forest canopy, even for high flight altitudes, making it possible to further increase the proportion of detected trees. Further research concerning the physical mechanism behind the interaction between the laser beams and tree crowns could also be useful to improve the existing retrieval algorithms. Detection of individual trees makes it possible to more directly measure tree size with high precision, therefore removing uncertainty from using only laser variables that are empirically related to tree attributes. However, because of the variability within forests, it will probably never be possible to detect all trees. One important research task is therefore to find out how tree detection methods can be combined with area based methods. The estimation units could be raster cells with approximately the same size as a field plot. Integration of field data with laser scanner data could be done by placing field plots within a sample of raster cells. Further research is needed to find out how laser data can be integrated with field data. For example, the effect of number of field plots and the size of the field plots should be investigated. Furthermore, the influence of forest types on the estimations should be studied. Also, field measurement methods would need to be developed in order to be more useful for calibration of the highly detailed laser measurements. For example field methods that allow efficiently positioning of trees. The raster cells as an estimation unit would allow for the use of forest information in a flexible way. The estimates of the raster cells could be aggregated to predefined forest stands. Airborne laser scanner data could be suitable for supporting automatic or semi-automatic delineation of forest stands because of the detailed laser measurements of tree height and forest density. The t-ratio segmentation method (Hagner, 1990) or one of the commercial segmentation routines could be applied. The basic idea with the t-ratio method is that spatially adjacent regions should be merged if they can not be separated with a given certainty. The possibility of using laser data for assessment of changes, for example, changes due to thinning or forest damages, should also be investigated.

Airborne laser scanners can be operated together with a digital camera or passive optical scanner. Methods should therefore be developed and validated for tree species discrimination by integrating the data sources, for example, by using co-registered high density laser scanner data and high resolution optical near infrared images. Features that could be extracted in the optical data include colour, texture, and branch structure parameters. Commercial airborne laser scanners operated today have been developed for terrain mapping and do not digitize the full returned waveform. However, if properties of the full returned pulse could be used, it would be possible to obtain more forest information than was possible to do in the studies reported in this thesis.

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