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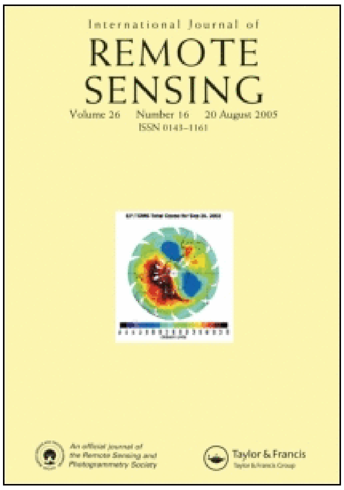

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J. Hyyppä [a]; H. Hyyppä [b]; D. Leckie [c]; F. Gougeon [c]; X. Yu [a]; M. Maltamo [d]
[a] Finnish Geodetic Institute, FIN-02431 Masala, Finland [b] Institute of Photogrammetry and Remote Sensing, Helsinki University of Technology, FIN-02015 Espoo, Finland [c] Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, V8Z 1M5, Canada [d] Faculty of Forestry, University of Joensuu, FIN-80101 Joensuu, Finland

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Review of methods of small-footprint airborne laser scanning for extracting forest inventory data in boreal forests

J. HYYPPÄ*†, H. HYYPPÄ‡, D. LECKIE§, F. GOUGEON§, X. YU† and M. MALTAMO¶

†Finnish Geodetic Institute, Geodeetinrinne 2, P.O. Box 15, FIN-02431 Masala, Finland
‡Institute of Photogrammetry and Remote Sensing, Helsinki University of Technology, P.O. Box 1200, FIN-02015 Espoo, Finland
§Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Road, Victoria, British Columbia, V8Z 1M5, Canada
¶Faculty of Forestry, University of Joensuu, P.O. Box 111, FIN-80101 Joensuu, Finland

Experiences from Nordic countries and Canada have shown that the retrieval of the stem volume and mean tree height of a tree or at stand level from laser scanner data performs as well as, or better than, photogrammetric methods, and better than other remote sensing methods. This paper reviews the methods of small-footprint airborne laser scanning for extracting forest inventory data, mainly in the boreal forest zone. The methods are divided into the following categories: extraction of terrain and canopy height model; feature extraction approaches (canopy height distribution and individual-tree-based techniques, techniques based on the synergetic use of aerial images and lidar, and other new approaches); tree species classification and forest growth using laser scanner; and the use of intensity and waveform data in forest information extraction. Despite this, the focus is on methods, some review of quality obtained, especially in the boreal forest area, is included. Several recommendations for future research are given to foster the methodology development.

1. Introduction

The rapid progress of remote sensing instruments provides scientists with new ways of solving conventional problems. Novel remote sensing applications can be developed in connection with the development of instruments with unique configuration. Therefore, the progress of the remote sensing instruments is one of the most significant 'driving' forces in the progress of new remote sensing applications.

Small-footprint airborne laser scanning (ALS) is a method based on laser range measurements (lidar, light detection and ranging) from an aircraft and the precise orientation of these measurements. The position and rotation of the sensor is continuously recorded using a differential global positioning system (GPS) and inertia measurement units (IMU) along the flight path. The ALS gives the georeferenced point cloud, from which it is possible to calculate digital terrain models (DTM), digital surface models (DSM) and three-dimensional (3D) models of object (e.g. the canopy height model). In addition to the point cloud data (files of x,

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*Corresponding author. Email: juha.hyyppa@fgi.fi

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y and z coordinates of the reflecting objects), the intensity and sometimes the full waveform of the target can be recorded. The pulse repetition frequency (PRF) of small-footprint airborne laser scanners is currently increasing rapidly. In 1993, the PRF was just 2 kHz, while today it is 200 kHz. Overviews of laser scanning can be found in Ackermann (1999), Baltsavias (1999), Wehr and Lohr (1999), and Wever and Lindenberger (1999), with future technological potential in Steinvall (2003).

In the 1960s, NASA used laser ranging for tracking of a corner cube reflector on the moon. In 1975, NASA and other organisations sponsored the development of the airborne oceanographic lidar (AOL) for measuring a variety of oceanographic properties such as chlorophyll and other biological and chemical substances. Non-scanning (non-imaging) laser rangefinders were used for several applications, especially bathymetry, in the 1970s and 1980s. Laser profilers were used in forest studies from around 1980 (e.g. Solodukhin *et al.* 1977, Nelson *et al.* 1984, Schreier *et al.* 1985, Aldred and Bonnor 1985, Maclean and Krabill 1986, Bernard *et al.* 1987, Currie *et al.* 1989) and the original concept of producing stand profiles with high-precision instruments was presented as early as 1939 (Hugershoff 1939).

Maclean (1982) proposed that the cross-sectional area of the forest canopy (stand profile) obtained via photointerpretation is related to the gross-merchantable volume. Nelson *et al.* (1984) suggested the use of the laser-derived stand profiles for the retrieval of stand characteristics. Since then, studies have been made of the use of laser measurements for estimating the tree height, stem volume and biomass (e.g. Nelson *et al.* 1984, Aldred and Bonnor 1985, Schreier *et al.* 1985, Maclean and Krabill 1986, Nelson *et al.* 1988, Currie *et al.* 1989, Nilsson 1990). Nelson *et al.* (1984) demonstrated that the elements of the stand profile are linearly related to crown closure and may be used to assess tree height. Schreier *et al.* (1985) stated that the near-infrared laser can produce terrain and vegetation canopy profiles and were the first to examine laser intensity for vegetation discrimination. Nelson *et al.* (1988) showed that the tree height, stem volume and biomass can be predicted with reasonable accuracy using ground-laser calibration plots and averaging. Aldred and Bonnor (1985), using waveform data, presented laser-derived tree height estimates within 4.1 m of the field-measured stand heights at a 95% level of confidence. Currie *et al.* (1989) measured the height of the flat-topped crowns with a standard error of about 1 m. Nilsson (1990) demonstrated that the data of a laser mounted on a boomtruck correlates with volume changes, such as thinnings. In order to obtain more information on the history of prior laser ranging measurements over forest, see, for example, Nelson *et al.* (1997), Nilsson (1996), including the first tests with the FLASH system to forestry, Lim *et al.* (2003) and Holmgren (2003).

The development of GPS combined with inertia measurements made it much easier to geometrically correct and reference lidar data. This greatly facilitated the development of operational methods. The first experiments with modern airborne scanning lasers were conducted in the early 1990s and in 1993, the first prototype of a commercial airborne lidar system dedicated to topographic mapping, was introduced.

In addition to small-footprint (0.2 to 2 m) airborne laser scanning, several large-footprint systems such as SLICER (scanning lidar imager of canopies by echo recovery), RASCAL (raster scanning airborne laser altimeter), and SLA 01/02 (shuttle laser altimeter I and II) have been developed. Because, today, mainly the small-footprint systems are commercially attractive, the discussion here will focus on small-footprint ALS.

The first studies of small-footprint ALS for forestry included the determination of terrain elevations (e.g. Kraus and Pfeifer 1998, Vosselman 2000), followed by standwise mean height and volume estimation (e.g. Næsset 1997a,b), individual-tree-based height determination and volume estimation (e.g. Hyyppä and Inkinen 1999, Brandtberg 1999, Ziegler *et al.* 2000), tree-species classification (e.g. Brandtberg *et al.* 2003, Holmgren and Persson 2004) and measurement of forest growth and detection of harvested trees (e.g. Hyyppä *et al.* 2003b, Yu *et al.* 2003, 2004b). Laser scanning experiences in Canadian, Norwegian, Swedish and Finnish forestry can also be found in Wulder (2003), Næsset (2003), Nilsson *et al.* (2003) and Hyyppä *et al.* (2003a). A Scandinavian summary of laser scanning in forestry can be read in Næsset *et al.* (2004). Since 2002, there have been annual meetings of laser scanning and forest mensuration societies. Examples of such conferences include: a workshop on the three-dimensional analysis of forest structure and terrain using lidar technology in Victoria; an Australian workshop on airborne laser altimetry for forest and woodland inventory and monitoring in Brisbane in 2002; Scandlaser 2003 in Umeå; Natscan 2004 in Freiburg; Silvilaser 2005 in Blacksburg, Virginia; 3D Remote Sensing in Forestry in Vienna 2006; Silvilaser 2006 in Matsuyama, Japan; and Laser Scanning 2007 and Silvilaser 2007 in Espoo. Articles on the development of methods can also be found in the papers of these conferences. There have been special issues on forestry and laser scanning in the Canadian Journal of Remote Sensing 2003, the Scandinavian Journal of Forest Research 2004, and Photogrammetric Engineering and Remote Sensing, December 2006.

About 100 years ago, forest inventory was considered to be the determination of the volume of logs, trees, and stands, and a calculation of the increment and yield. More recently, forest inventory has expanded to cover assessment of various issues including wildlife, recreation, watershed management and other aspects of multiple-use forestry. However, a major emphasis of forest inventory still lies in obtaining information on the volume and growth of trees, forest plots, stands and large areas. This paper reviews the methods and quality of small-footprint airborne laser scanning for extracting forest inventory data, with a greater focus on boreal forest examples. Concerning quality and accuracy, it should be understood that the reported results are subject to site conditions.

2. Extraction of the digital terrain model

Since laser scanning can provide 3D characterisation of forest canopies, the basics for modern ALS-based forest measurements rely on the acquisition of the DTM (digital terrain model) corresponding to the ground surface and the DSM (digital surface model) corresponding to treetops. The errors in the DTM will result in errors of tree height.

2.1 *Methods*

Photogrammetrists have developed various methods for obtaining DTMs from laser scanning point clouds. Kraus and Pfeifer (1998) developed a DTM algorithm based on distinguishing laser points between terrain points and non-terrain points using an iterative prediction of the DTM and weights attached to each laser point, depending on the vertical distance between the expected DTM level and the corresponding laser point. Pyysalo (2000) developed a modified recursive classification method for DTM extraction, where all points within a 60 cm vertical distance from the lowest expected ground level were included equally in the next DTM model calculation. Axelsson (1999, 2000, 2001) developed a progressive TIN densification method where the surface was allowed to fluctuate within certain values, controlled by minimum description length, constrained spline functions and active contour models for elevation differences. Ground points were connected in a TIN. A sparse TIN was derived from neighbourhood minimum, and then progressively densified to the laser point cloud. At every iteration, points are added to the TIN, if they are within the defined thresholds. The method has been implemented for TerraScan software (see www.terrasolid.fi). Elmqvist *et al.* (2001) estimated the ground surface by employing active shape models using energy minimisation. The start state is a plane below the lowest point in the dataset. The active shape model behaves like a membrane floating up from underneath the data points. The energy function is a weighted combination of internal and external forces. Sithole (2001) and Vosselman and Maas (2001) developed a slope-based filtering technique that works by pushing up vertically a structuring element. In the method used by Wack and Wimmer (2002), non-terrain raster elements are detected in a hierarchical approach that is loosely based on a block-minimum algorithm. The comparison of the filtering techniques used for DTM extraction can be found in a report on the International Society for Photogrammetry and Remote Sensing (ISPRS) comparison of filters (Sithole and Vosselman 2004). The selection of the filtering strategy is not a simple process. In practice, the amount of interactive work determines the final quality of the product. Examples of commercial software that include DTM generation are REALM, TerraScan, LidarEngine and SCOP++.

2.2 *Factors affecting the quality of the DTM*

Describing the height accuracy of laser-derived DTMs with a bias and a standard error is, in most cases, not sufficient. Due to the integration of different sensors (GPS, INS, laser scanner), the height error budget of a single laser point is a combination of several error components (Crombaghs *et al.* 2002). These errors can be roughly divided into four components: an error per point; error in a strip section (covered during one GPS observation); error per strip; and error within an entire block. However, in addition to errors caused by the laser system and errors caused by the applied methodology and algorithms (for an algorithm comparison see Sithole and Vosselman (2004)), the quality of a DTM derived from laser scanning is influenced by data characteristics (e.g. point density, first/last pulse, flight height, scan angle), as well as errors due to characteristics of the complexity of the target (type of terrain, flatness of terrain, density of the canopy above, amount and height of ground vegetation or understorey). Test flights (TopoSys 1996) have shown that, at scanning angles of more than 10° off-nadir, the amount of shadowed areas increases considerably, i.e. the number of measured ground hits decreases and gaps in the DTM occur more frequently. With regard to type of terrain and surface, Raber *et al.* (2002a) and Hodgson *et al.* (2003) found that land-cover types (e.g. scrub/shrub) were a significant factor that influences the accuracy of a laser DTM in forested areas. Terrain-slope impact on a laser DTM was examined by Hyyppä *et al.* (2000) and Hodgson *et al.* (2003). Raber *et al.* (2002a) suggested that when information about the terrain type or land cover is known, it can be used in the filtering to improve the accuracy of the resultant DTM. In addition, data obtained in leaf-off conditions were found to be more suitable to map the terrain surface than data obtained in leaf-on conditions (Raber *et al.* 2002b). Results from these earlier studies suggest that better accuracy was obtained in open, flat areas. With an increase in the vegetation cover or terrain slope, accuracy deteriorated. It seems that forest canopy and understorey vegetation cover are 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. Practical tests have shown that laser scanning data always includes low points under the ground level. These may be real returns or distortions due to strong backscatters (as reported with profiling microwave radar by Hyyppä (1993)). Filtering of low erroneous points iteratively is the preferred procedure before the final DTM calculation. Errors will also sometimes arise as, in dense ground vegetation, it is not always possible to separate the ground hits from the ground vegetation, which can cause an offset in the DTM, and the DTM surface will follow the ground vegetation surface rather than the ground surface.

2.3 *Quality of the DTM*

Kraus and Pfeifer (1998) reported a root mean square error (RMSE) of 57 cm in the DTM elevations for wooded areas using ALTM 1020 and an average point spacing of 3.1 m. Hyyppä *et al.* (2000) reported a random error of 22 cm for fluctuating forest terrain using TopoSys-1 and a nominal pulse density of 10 pulses per m^2. Within the European Commission funded HIGH-SCAN project (1998 to 2001), three different DTM algorithms were compared in Finnish (test site Kalkkinen, nominal point density 10 points per m^2), Austrian (Hohentauern, density 4 to 5 points per m^2) and Swiss (Zumikon, density 4 to 5 points per m^2) forests. The random errors obtained in the DTM varied between 22 and 40 cm (Hyyppä *et al.* 2001) using TopoSys-1. Ahokas *et al.* (2002) compared three algorithms in forested hilly terrain in Finland and found random errors between 13 and 41 cm using TopoSys-1. Reutebuch *et al.* (2003) reported random errors of 14 cm for clearcut, 14 cm for heavily thinned forest, 18 cm for lightly thinned forest, and 29 cm for uncut forest using TopEye data with 4 pulses per m^2. However, in dense forests, errors of up to 10 to 20 m can occur in the DTM estimation (Takeda 2004). Results described in a paper by Hyyppä *et al.* (2005) can be used to optimise the laser flight with respect to the desired quality. The paper analysed the effects of the date, flight altitude, pulse mode, terrain slope, forest cover and within-plot variation on the DTM accuracy in the boreal forest zone. The following conclusions could be drawn from the high-density data. In the boreal forest zone, random errors of less than 20 cm can be obtained in most conditions for non-steep (slope angle less than 20°) terrain with a pulse density of better than 2 points per m^2. The increase in flight altitude from 400 (8 to 10 points per m^2) to 1500 m (2 to 3 points per m^2) increased the random error in the DTM derivation from 12 to 18 cm (i.e. 50%). Thus, the improvement of DTM errors by a factor of two requires a significant increase in the PRF. The difference in using the first or last pulse causes a corresponding random error difference, i.e. 5 cm. Thus, even the first pulse data are applicable for DTM derivation in boreal coniferous areas. There can be systematic shifts in the elevation models derived at various flight altitudes. The systematic errors increase when the flight altitude increases. It is thought that the beam size, triggering algorithms and sensitivity of the laser system determine this systematic behaviour. Additionally, the systematic shifts between the last and first pulse are significant. The difference in DTMs derived at optimum (leaf-off) and non-optimal season (leaf-on) conditions at boreal coniferous-dominated forests is typically less than 5 cm with high-density data. Thus, forest DTM derivation can also be carried out in summer conditions. In a stand consisting of deciduous trees, the effects are, of course, the highest. Use of leaf-on conditions reduces the accuracy of the DTMs. The closer the trunk, the greater the effect of the forest. The random error is 2 to 5 cm higher near the trunk compared to the gap area. The results are site-dependent, i.e. the accuracy varies as a function of site conditions (slopes, undergrowth, forest cover). The final quality of the DTM is determined by the density of penetrated points on the ground, underground vegetation density and slope angle. Ahokas *et al.* (2005) proposed that the optimisation of the scanning angle (i.e. field of view) is an important part of countrywide laser scanning. Significant savings can be obtained by increasing the scanning angle and flight altitude. The very first results obtained with a scanning angle analysis showed that the scanning angle had an effect on the precision, but other factors, such as forest density, dominate the process. Scanning angles up to 15° seem to be usable for high-altitude laser scanning in the boreal forest zone. Ahokas *et al.* (2005) pointed out that the effects of the scanning angle should be further studied. For comparison, the maximum field of view of Optech ALTM 3100EA is 50° and the corresponding value for ALS50-II of Leica is 75°.

3. Extraction of canopy height

3.1 *Methods*

The most appropriate technique to obtain a DSM relevant to treetops is to classify the highest reflections (i.e. by taking the highest point within a defined neighbourhood) and interpolate missing points, for example by Delaunay triangulation. The canopy height model (CHM) is then obtained by subtracting the DTM from the corresponding DSM. This is also called a normalised DSM (nDSM). The crown DSM is typically calculated by means of the first pulse echo and the DTM by the last pulse echo. In order to guarantee that there are no systematic errors between the first and last pulse data, calibration using flat, non-vegetated areas, such as roads, roofs, and sports grounds should be performed. This is especially necessary when laser scanning systems require separate first and last echo recordings and both echoes are used for separate models.

When working with point clouds, the processing of the point cloud data into canopy heights or normalised heights is an effective way of increasing the usability of the laser data. Laser canopy heights are simply calculated as the difference between elevation values of laser hits and estimated terrain elevation values at the corresponding location.

3.2 *Factors affecting the quality of the CHM*

It was already noticed in the 1980s using small-footprint systems that the use of a laser leads to an underestimation of tree height. That was obvious with the use of profiling lasers, since it was expected that the laser was mainly hitting the tree 'shoulder' rather than the treetops (e.g. Nelson *et al.* 1988). Thus, detection of the uppermost portion of a forest canopy is expected to require a sufficient density of laser pulse footprints to sample the tree tops and a sufficient amount of reflecting material occupying each laser pulse footprint to cause a detectable return signal (e.g. Lefsky *et al.* 2002). If the ground elevation and/or the uppermost portion of a forest canopy are not detected, then the canopy height will be underestimated. Lefsky *et al.* (2002) also expected the sampling density to be the principal issue determining whether the canopy height with a small-footprint ALS is underestimated. Previously, tree height underestimation has been reported for individual trees and for both deciduous and coniferous trees (Hyyppä and Inkinen 1999, Persson *et al.* 2002, Gaveau and Hill 2003, Leckie *et al.* 2003, Yu *et al.* 2004a, 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 affected by: the density and coverage of laser pulses; the algorithm used to obtain the canopy height model; the amount and height of undervegetation; the algorithm used to calculate the digital terrain model; the sensitivity of the laser system and thresholding algorithms used in the signal processing as well as pulse penetration into the canopy; and the tree shape and tree species. Finding a universal correction factor for the underestimation may be difficult, 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 Rönnholm *et al.* (2004) demonstrated the use of terrestrial image data in the 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. The model explained why the estimation of stand heights from laser scanner data based on maximum canopy height value in each cell of a fixed area grid (e.g. Næsset 1997b) has been successful in practice.

3.3 *Quality of canopy height models analysed using individual trees*

Examples of reported tree underestimation values and the accuracy of individual tree assessments are given below. They concern assessments where errors have not been calibrated or compensated for with reference data. For a comparison of mean tree height obtained in a forest inventory, see Næsset *et al.* (2004) for example.

Hyyppä and Inkinen (1999) reported individual tree height estimation with an RMSE of 0.98 m and a negative bias of 0.14 m (nominal pulse density about 10 pulses per m^2), while Persson *et al.* (2002) reported an RMSE of 0.63 m and a negative bias of 1.13 m. Both test sites were dominated by Norway spruce and Scots pine. Persson *et al.* (2002) further explained their greater underestimation of the average tree height as resulting from a lower ALS sampling density (about 4 pulses per m^2). Næsset and Økland (2002) stated that the estimation accuracy was significantly reduced by a lower sampling density. Gaveau and Hill (2003) reported on the estimation of tree height in broadleaf woodland, since previous studies had concentrated on coniferous forests. A negative bias of 0.91 m for sample shrub canopies and 1.27 m for sample tree canopies was observed. Leckie *et al.* (2003) concluded that some of the 1.3 m underestimation could be accounted for by the undergrowth. Yu *et al.* (2004a) found a systematic underestimation of tree heights of 0.67 m for the laser acquisition carried out in 2000 and 0.54 m for another acquisition in 1998. The underestimation corresponded to 2 to 3 years of annual growth by those trees. Of that, the elevation model overestimation (due to undervegetation) was assumed to account for about 0.20 m. Maltamo *et al.* (2004) used 29 pines accurately measured with a tacheometer, which can give more precise field measurements than conventional methods, and found a 0.65 m underestimation of the height for single trees, including annual growth that was not compensated for in the plot measurements. They also found that the precision of 0.50 m for individual tree height measurements was better than reported earlier (e.g. Hyyppä and Inkinen 1999, Persson *et al.* 2002). In the studies of Rönnholm *et al.* (2004) and Brandtberg *et al.* (2003), it was shown that the tree height can also be reliably estimated even under leaf-off conditions for deciduous trees.

3.4 *Experimental results of the effect of flight altitude, pulse density and footprint size on canopy height*

Yu *et al.* (2004a) evaluated the effect of laser flight altitude on the tree height estimation at individual tree level in a boreal forest area mainly consisting of Norway spruce, Scots pine and silver and downy birch. The test area (0.5 × 2 km) was flown over at three altitudes (400, 800 and 1500 m) with a TopoSys-II scanner (beam divergence 1 mrad) in spring 2003. A field inventory was carried out on 33 sample plots (about 30 × 30 m) in the test area during summer 2001. Evaluations of estimation errors due to flight altitudes, including beam size and pulse density, were performed for different tree species. The results indicate, in general, that the accuracy of the tree height estimation decreases (from 0.76 to 1.16 m) with the increase in flight height (from 400 m to 1.5 km). The number of detectable trees also decreases. Point density had more influence on the tree height estimation than footprint size; for more details see Yu *et al.* (2004a). Birch trees were less affected than coniferous trees by the change in the flight altitude in this study. Persson *et al.* (2002) reported that the estimates of tree height were not affected much by different beam diameters ranging from 0.26 to 2.08 m. With a larger beam diameter of 3.68 m acquired at a 76% higher altitude, the underestimations of tree heights were greater than with other beam diameters, which is probably due to the decreased pulse density. Nilsson (1996) did not find any significant effects of beam divergence on the height estimates over a pine-dominated test site. Aldred and Bonnor (1985) reported increased height estimates as the beam divergence increased, especially for deciduous trees. In the study conducted by Næsset (2004), it was concluded that first pulse measurements of height are relatively stable regardless of flight altitude/beam size, at least when the beam size varies in the 16 to 26 cm range. Goodwin *et al.* (2006) used three different platform altitudes (1000, 2000 and 3000 m), two scan angles at 1000 m (10° and 15° half maximum angle off nadir), and three footprint sizes (0.2, 0.4 and 0.6 m) in eucalyptus forests at three sites, which varied in vegetation structure and topography. They observed no significant difference between the relative distribution of laser point returns, indicating that platform altitude and footprint size have no major influence on canopy height estimation. They also reported that higher platform altitudes record a lower proportion of first/last return combinations that will further reduce the number of points available for forest structural assessment and development of digital elevation models. For discrete lidar data, increasing platform altitudes will record a lower frequency of returns per crown resulting in larger underestimates of the individual tree crown area and volume.

The results seem to indicate, that relatively good canopy height information can be collected with various parameter configurations; pulse density is today expected to be the key parameter on the level of the inventory – this topic is discussed more in the next section.

4. Main feature extraction approaches

The two main feature extraction approaches for deriving forest information from laser scanner data have been those based on statistical canopy height distribution and individual tree detection. These categories relate to the need for scale and accuracy of the forestry information and available point density. Both approaches use the CHM or the processed point clouds into canopy heights described in §3.1. In the distribution-based techniques, features and predictors are assessed from the laser-derived surface models and canopy height point clouds, which are directly used for forest parameter estimation, typically using regression, non-parametric or discriminant analysis. In the individual-tree-based approaches, the neighbourhood information of canopy height point clouds and pixels of 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 is then calculated or estimated using existing models and statistical techniques or a compilation of individual tree information.

4.1 *Extraction of forest variables by canopy height distribution*

Maclean (1982) proposed that the cross-sectional area of the forest canopy, i.e. the canopy profile area, is directly related to the logarithm of the timber volume. Maclean and Krabill (1986) suggested that the modified canopy profile, consisting of all laser height measurements above a certain exclusion limit, would predict volume more accurately than the entire canopy profile.

Height percentiles of the distribution of canopy heights have been used as predictors in regressions or non-parametric models for the estimation of the mean tree height, basal area and volume (e.g. Næsset 1997a,b, Lefsky *et al.* 1999, Magnussen *et al.* 1999, Means *et al.* 1999, Lim *et al.* 2002, Næsset 2002, Næsset and Økland 2002, Hopkinson *et al.* 2006, Maltamo *et al.* 2006b). In addition to the prediction of stand mean and sum characteristics, diameter distributions of a forest stand have also been predicted by using the statistical canopy-height-distribution-based approach (e.g. Gobakken and Næsset 2005, Maltamo *et al.* 2006a). In Means *et al.* (1999), a large-footprint scanning lidar SLICER was used in the estimation of the tree height, basal area and biomass in Douglas-fir-dominated forests, with the tree height ranging from 7 to 52 m, with a coefficient of determination values of 0.95, 0.96 and 0.96, respectively. In addition to canopy height information, canopy reflection sum, ground reflection sum and canopy closure were used. The canopy reflection sum is the sum of the portion of the waveform return reflected from the canopy, whereas the ground reflection sum is the sum of waveform return reflected from the ground multiplied by a factor correcting for the canopy attenuation. Canopy closure was approximated by dividing the sum of the canopy and ground reflection sums. In Næsset (2002), several forest attributes were estimated using canopy height and canopy density metrics using a two-stage procedure and field data. Canopy height metrics included, for example, quantiles corresponding to the 0, 10, …, 90 percentiles of the first pulse laser canopy heights and corresponding statistics, whereas canopy density corresponded to the proportions of both the first and last pulse laser hits above the 0, 10, …, 90 quantiles to total number of pulses.

In Riaño *et al.* (2003), several statistical parameters were defined for forest fire behaviour modelling: tree cover was calculated from the proportion of laser hits from the tree canopy divided by the total number of laser hits; surface cover was defined as the proportion of laser hits from the surface and the total number of hits; crown bulk density was obtained from the foliage biomass estimates and crown volume by using an empirical equation for foliage mass; and crown volume was estimated as the crown area times the crown height after a correction for mean canopy cover.

In Holmgren and Persson (2004), a large number of height- and intensity-based variables were defined for tree species classification, for example: relative standard deviation of tree heights; the proportion of single returns and the proportion of first return, as well as the proportion of vegetation points (the number of returns that were located above the crown base height divided by the total number of returns from the segment); crown shape by fitting a parabolic surface to the laser point cloud; and mean intensity and standard deviation of both single and surface returns. They showed an overall classification accuracy of 95% between Scots pine and Norway spruce. High classification accuracy was obtained by using the proportion of first returns and the standard deviation of the intensity. There was also a strong correlation between the standard deviation of laser heights within a segment and the corresponding crown base height, and between the mean distance between first and last return of a double return within a segment and the corresponding crown length was found. In Hall *et al.* (2005), 39 metrics were similarly derived from the lidar data.

Examples of the accuracy of techniques based on canopy height distribution can be found in Næsset *et al.* (2004). In Hollaus (2006), the distribution-based technique was tested for the highly structured alpine forests. It was stated that for this pure statistical approach, the multiple regression analyses lead to different sets of independent variables if ALS data with different acquisition times or point densities are used for the calculations. Therefore, Hollaus (2006) recommended that, for ALS datasets with different properties (e.g. point densities, acquisition times), separate regression models should be used. The proposed linear approach in Hollaus (2006) was based on original work of Nelson *et al.* (1984, 1988) and adapted from two-dimensional (2D) canopy profiles to three-dimensional (3D) canopy heights. It showed that for ALS data with varying properties, robust and reliable results of high accuracies (e.g. $R^2=0.87$, standard deviation of the stem volume residuals derived from a cross-validation is $90.0\,\mathrm{m}^3\,\mathrm{ha}^{-1}$) can be achieved. Due to the simplicity of this linear model, a physically explicit connection between the stem and the canopy volume is available.

4.2 *Extraction of individual-tree-based information*

Recent developments in the computer analysis of high spatial resolution (<1 m per pixel) images are leading towards the semi-automated production of forest inventories based on individual tree crown information. The extraction of individual-tree-based information from remote sensing can be divided into finding tree locations, finding tree locations with crown size parameterisation, or full crown delineation (Pouliot *et al.* 2002, Gougeon and Leckie 2003). The methods used in laser scanning can utilise the methods already developed using high- and very-high-resolution aerial imagery. Additionally, in laser scanning it is possible to improve the image-based approaches by using the powerful ranging algorithms and knowledge-based approaches (e.g. we know the tree height and we can roughly estimate the size of the crown).

Tree locations can be obtained by detecting image local maxima (e.g. Gougeon and Moore 1989, Dralle and Rudemo 1996, Wulder *et al.* 2000). In laser scanning, the aerial image is replaced by the crown DSM, the canopy height model or the normalised point cloud. Provided that the filter size and image smoothing parameters are appropriate for the tree size and image resolution, the approach works relatively well with coniferous trees (e.g. Gougeon and Leckie 2003). After local maxima have been found, the edge of the crown can be found using region segmentation, edge detection or local minima detection (e.g. Pinz 1991, Uuttera *et al.* 1998, Culvenor 2002). 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), or region growing (Erikson 2003). In laser scanning, the individual tree approach typically provides tree counts, tree species, crown area, canopy closure, gap analysis, and volume or biomass estimation (Hyyppä and Inkinen 1999, Gougeon and Leckie 2003).

Hyyppä and Inkinen (1999), Friedlaender and Koch (2000) and Ziegler *et al.* (2000) demonstrated the individual-tree-based forest inventory using laser scanner tree finding with maxima of the CHM and segmentation for edge detection. They also presented the basic lidar-based individual tree crown approach in which tree height, crown diameter and species are derived from individual tree locations, using a laser, possibly in combination with aerial image data, especially for tree species classification. Then, other important variables, such as stem diameter, basal area and stem volume, are derived using existing models. The methods were tested in Finnish, Austrian and German coniferous forests and 40% to 50% of the trees could be correctly segmented (Hyyppä *et al.* 2001). Persson *et al.* (2002) improved the crown delineation and could link 71% of the tree heights with the reference trees. Other attempts to use DSM or CHM images for individual tree crown (ITC) isolation or crown diameter estimation have been reported (e.g. Brandtberg *et al.* 2003, Leckie *et al.* 2003, Popescu *et al.* 2003, Straub 2003, Falkowski *et al.* 2006, Tiede and Hoffmann 2006). Andersen *et al.* (2002) proposed fitting ellipsoid crown models in a Bayesian framework to the point cloud. Morsdorf *et al.* (2003) presented a practical two-stage procedure where tree locations were defined using the DSM and local maxima, and crown delineation was performed using *k*-means clustering in the three-dimensional point cloud. Wack *et al.* (2003) firstly calculated the canopy height corresponding to all laser points and used a sorted list technique to process the trees in decreasing height order. The process was recursive. Out of the planted eucalyptus trees, 93% could be correctly delineated in this manner. Pitkänen *et al.* (2004) presented three methods for individual tree detection: smoothed CHM with the knowledge of the canopy height; elimination of candidate tree locations based on the predicted crown diameter and distance and valley depth between two locations studied (maxima elimination); and the modified scale–space method used for blob detection. The maximum elimination method gave the best results of tree detection, however, with the cost of including several parameters to keep the number of false positives low. Sohlberg *et al.* (2006) presented new methods for controlling the shape of crown segments, and for residual adjustment of the canopy height model. The method was applied and validated in a Norway-spruce-dominated forest having heterogeneous structure. The number of trees detected varied with social status of the trees, from 93% of the dominant trees to 19% of the suppressed trees.

4.3 *Comparison of canopy-height-distribution- and individual-tree-based methods*

Canopy height distribution approaches use the distribution of laser canopy heights to estimate stand heights. Individual tree methods, on the other hand, are focused on determining the heights of individual trees. The expectation with individual tree methods is that height can be determined with no or with a consistent bias such that no project- or site- specific calibration is needed. Therefore, the methods would be independent of the stand specific tree distribution, shapes, species and heights that affect canopy distribution methods and necessitate varying degrees of calibration.

There has not been a careful comparison of canopy-height-distribution- and individual-tree-based techniques; results obtained have been based on different types of reference datasets. Typically, distribution-based techniques have been calibrated with very large and accurate reference data and individual-tree-based approaches have not been calibrated at all. Thus, the study results obtainable are not comparable, even though a summary of the obtainable accuracy can be found in Næsset *et al.* (2004). A short overview of the general advantages and disadvantages of the techniques are given in table 1. In the practical implementation of individual-tree-based techniques, calibration data, either at tree level or plot level, is recommended to calibrate systematic errors in the applied models and to improve the volume and diameter estimation.

4.4 *Other possible inventory approaches*

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

4.4.1 Tree-cluster-based inventory. Depending on the density of the forest and density of the point clouds, the discrimination of individual trees is a problem of varying complexity. In dense stands, this leads to an underestimation of the number of tree stems. What if the individual-tree-based technique is applied directly to tree clusters?

Bortolot (2006) proposed a tree cluster approach, which consists of calculating the percentage of grid pixels that are in tree clusters, the percentage of cluster pixels that are core pixels, the mean height of the cluster pixels and the standard deviation of the cluster pixels from the canopy height model. Core pixels were those pixels that were fully surrounded by the cluster pixels. The percentage of core pixels referred to cases where many trees are joined together. The percentage of core pixels and mean height metrics appeared to be the best for predicting density and biomass.

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

	Advantages	Disadvantages
Distribution-based methods	Easy to integrate with present forest inventory practices due to common reference plots.	Requires extensive, accurate, representative and expensive reference data.
	Strong statistical approach used.	Without a large amount of reference data, strong possibility of large errors in operational inventories.
	Laser scanning data relatively inexpensive.	
Individual-tree-based methods	Good physical correspondence (existing models) with volume estimation.	More expensive laser data.
	Low amount of reference data needed for calibration.	More complex system to implement.
	Allows precision forestry and increased amount of information on the forests.	

Preliminary results showed better performance over the applied individual-tree-based technique.

Hyyppä *et al.* (2006) proposed that a cluster-based technique using the individual-tree-based approach, low-density laser data, and by calculating the corresponding number of trees in the large segment based on statistics or by using the existing volume model to account for the large segment. The results indicated that individual tree volumes can be obtained, with random errors of about 30% and the volume related to small tree clusters or segments with a random error of 37%.

4.4.2 Using the synergy of aerial images and laser scanning. The integration of laser scanning and aerial imagery can be based on simultaneous or separate data acquisitions. There is high synergy between the high-resolution optical imagery and laser scanner data for extracting forest information. Laser data provides accurate height information, which is missing in non-stereo optical imagery, and also supports information on the crown shape and size depending on pulse density, whereas optical images provide more details about spatial geometry and colour information usable for classification of tree species and health.

St-Onge (1999) used multi-spectral digital videography to verify the laser scanning accuracy for height estimation. The height of individual trees read from the laser-derived CHM at the centre of the tree crowns visible on the overlaid multi-spectral imagery were compared with field observations consisting of the mean of the two height measurements for each GPS-positioned tree.

Gougeon *et al.* (2001) discussed the synergy between aerial and lidar data and found that the lidar data, when used as a filter to the aerial data or on its own, made extremely obvious (and intuitive) the distinction between the dominant/codominant level and the understorey level, or regeneration versus ground vegetation, thus permitting separate analyses. They also found that using a height-based threshold, the valley-following-based crown delineation algorithm is able to function (on aerial or lidar CHM) in wide-open and low-density areas (visual first order logic with multi-spectral scanner data is limited to medium to densely forested areas because it requires a blanket of shade between the trees, unless there is a way to mask the ground vegetation by multi-spectral pre-processing rules), and valley-following-based crown delineation in the optical part of the spectrum is usually hampered in a direction perpendicular to the illumination angle (i.e. no shade between crowns). Similarly, delineation from a lidar-acquired canopy height model is hampered in the direction of the scan (off nadir), the synergistic effect of using the two datasets leads to more crowns being properly delineated (i.e. fewer tree clusters).

Persson *et al.* (2004) combined laser data with high-resolution near-infrared digital images using a segmented laser-derived CHM and camera position and orientation (roll, pitch and heading) of each aerial image to map each tree segment derived from the laser data to the corresponding pixel in the aerial image. Leckie *et al.* (2003) applied a valley-following approach to individual tree isolation of both digital frame camera imagery and a canopy height model created from high-density lidar data. The results indicate that optical data may be better at outlining crowns in denser situations, and thus more weight should be given to optical data in these situations. Lidar also easily eliminated most of the commission errors that often occur in open stands with optical imagery.

Maltamo *et al.* (2006b) compared the ability of laser scanner data and aerial images, as well as a combination of these data sources, to predict forest resource information by using a canopy height distribution approach. A non-parametric k-most similar neighbour application was constructed for the prediction of the plot and stand volumes of standing trees. The accuracy of laser scanning was superior compared to aerial images, but the combination of the data sources further slightly improved the results.

There are several versions of individual-tree-based methods using the combination of aerial images and laser data. It has been shown that a laser gives a more reliable tree height than photogrammetry for example, since the ground surface is often obscured on aerial images and it is difficult to measure tree heights. Alternative ways of obtaining the tree height for individual trees are: (1) subtracting the old laser-derived DTM from the DSM of tree tops obtained using stereophotogrammetry (as proposed by St-Onge *et al.* (2004)) and (2) interpolating a corresponding tree height from the low-density-derived CHM. The tree height information can then be joined with a properly segmented aerial image. In Hyyppä *et al.* (2005), an aerial image was segmented and the tree height for each tree was obtained from a laser CHM. The accuracy of the inventory was comparable with that carried out with a high-density laser, individual-tree-based technique and there was a significant improvement over the performance compared with the fully aerial-image-based approach.

Suarez *et al.* (2005) proposed a segmentation method using a data fusion technique available from eCognition to identify individual trees using scale and homogeneity parameters from the image and the elevation values from the CHM. The segmentation process resulted in the aggregation of pixels sharing similar characteristics in terms of reflectance and elevation. The object primitives were classified according to an empirically-defined, rule-based system aiming to identify tree tops. The purpose of this classification was to combine the segments (primitives) into units representative of tree crowns. The classification was based on a fuzzy logic classification system where membership functions apply thresholds and weights for each data layer. Elevation in the CHM was weighted five times more than each layer in the visible bands in order to strengthen the importance of elevation compared with the three colour bands.

4.4.3 Combining distribution-based techniques with individual-tree-based techniques. A novel approach to improve the quality of the individual-tree-based inventory was proposed by Villikka *et al.* (2007). They proposed the use of tree-level laser-height distribution characteristics of individual trees combined with conventional variables of individual tree recognition (height, diameter at breast height) for improving the prediction of individual tree stem volume. It is worth noting that approximate tree height and crown diameters were used in all of the constructed models, but the lower height quantiles and corresponding crown densities also have an additional statistical explanation for the considered tree characteristics.

4.5 *Derivation of the suppressed tree storey*

The possibility of characterising suppressed trees is a new research area. The original point clouds (instead of DSMs or CHMs) need to be used from this. Since some of the laser pulses will penetrate under the dominant tree layer, it may be possible to analyse multi-layered stands. For example, Zimble *et al.* (2003) demonstrated that laser-derived tree height variances could be used to distinguish between single-storey and multi-storey classes. In Maltamo *et al.* (2005), the existence and number of suppressed trees were examined. This was carried out by analysing the height distributions of reflected laser pulses. The histogram thresholding method of Lloyd was applied to the height distribution of laser hits in order to separate different tree storeys. Finally, the number and sizes of suppressed trees were predicted with estimated regression models. The results showed that multi-layered stand structures can be recognised and quantified using quantiles of laser scanner height distribution data. However, the accuracy of the results is dependent on the density of the dominant tree layer.

5. Tree species classification with lidar

In many forest applications, tree species is of particular interest as an essential index in forest studies, inventories and managements. At present, species classification can be accomplished using both optical/near-infrared and laser data.

Conventionally, tree species information is extracted from high-spatial-resolution colour infrared aerial photographs (e.g. Brandtberg 2002, Bohlin *et al.* 2006). The airborne laser scanning data has also been tested for tree species classification. Holmgren and Persson (2004) tested species classification of Scots pine and Norway spruce using laser scanner data (point spacing 0.4 to 0.5 m) at individual tree level. The proportion of correctly classified trees on all the plots was 95%. Moffiet *et al.* (2005) proposed that the proportion of laser singular returns is an important predictor for the tree species classification (poplar box and Cypress pine). While a clear distinction between these two species was not always visually obvious at the individual tree level, due to other extraneous sources of variation in the dataset, the observation was supported, in general, at the site level. Sites dominated by poplar box generally exhibited a lower proportion of singular returns compared to sites dominated by Cypress pine. Brandtberg *et al.* (2003) used laser data under leaf-off conditions for the detection of individual trees, and tree species classification results using different indices suggest a moderate to high degree of accuracy in deciduous species classification. Persson *et al.* (2006) identified individual tree species through combining features of high-resolution laser data (50 pulses per m^2) with high-resolution multi-spectral images (ground resolution 0.1m). Tree species classification experiments were conducted in southern Sweden in a forest dominated by Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and deciduous trees, mainly birch (*Betula* spp.). The results implied that by combining a laser-derived structure and spectral features, the classification could be improved and accuracies of 95% were achieved. Liang *et al.* (2007) used a simple technique, the difference of the first and last pulse return under leaf-off conditions, to discriminate between deciduous and coniferous trees at individual tree level. A classification accuracy of 90% was obtained.

Packalén and Maltamo (2007) used a combination of laser scanner data and aerial images to predict species specific plot level tree volumes. A non-parametric k-most similar neighbour application was constructed by using characteristics of the canopy height distribution approach of laser data and textural and spectral values of aerial image at plot level.

6. Forest growth

6.1 *Methods for forest growth*

Tree growth consists of the elongation and thickening of roots, stems and branches (Husch *et al.* 1982). Growth causes trees to change in weight, volume and shape (form). Usually, only the growth of the tree stem is considered by using the growth characteristics of the tree, diameter, height, basal area and volume. In most cases, volume growth is the most interesting characteristic and it has to be derived from the change in other characteristics. Traditionally, height and diameter growth of individual trees are determined in the field from repeated measurements of permanent sample plots and from increment core measurements (e.g. boring), see Husch *et al.* (1982).

Laser-data-based methods for forest growth are, in principle, relatively simple. The height growth can be determined by several means: from the difference in the height of individual trees determined from repeated measurements (Yu *et al.* 2003); from the height difference of repeated DSMs (Hirata 2005); and from repeated height histograms (Næsset and Gobakken 2005). But, in practice, 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. The technique applied should be able to separate growth from other changes in the forest, especially those due to selective thinning or due to naturally fallen trees. The difference between DSMs is assumed to work in areas with wide and flat-topped crowns, but in coniferous forests with narrow crowns, the planimetric displacement between two acquisitions can be substantial. Height histograms can be applied to point clouds corresponding to individual trees or plots or stands, but the information contents of histograms are corrupted if thinning has occurred.

6.2 *Quality of ALS growth analysis and change detection*

Yu *et al.* (2003, 2004b) demonstrated the application of laser data to forest growth in a preliminary fashion without good reference data at plot and stand level using an object-oriented tree-to-tree matching algorithm and statistical analysis. St-Onge and Vepakomma (2004) concluded that sensor-dependent effects, such as the threshold for triggering a response, are 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, especially over long-term intervals. Næsset and Gobakken (2005) concluded that, over a 2 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 per m^2 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 maximum height tends to be less stable. Yu *et al.* (2005) reported that height growth for individual trees can be measured with an accuracy better than 0.5 m using multi-temporal laser surveys conducted in a boreal forest zone for a 4 year time series.

In Yu *et al.* (2006), 82 sample trees were used to analyse the potential of measuring individual tree growth of Scots pine in the boreal forest. Point clouds, having 10 points per m^2 and illuminating 50% of the tree tops, were acquired in September 1998 and May 2003 with the TopoSys 83 kHz lidar system. Three variables were extracted from the point clouds representing each tree: the difference of the highest z value; the difference between the DSMs of tree tops; and the difference of the 85%, 90% and 95% quantiles in the height histograms corresponding to a crown. An R^2 value of 0.68 and standard deviation of 43 cm was obtained with the best model. The results indicate that it is possible to measure the growth of an individual tree with multi-temporal laser surveys. They also demonstrated a new algorithm for tree-to-tree matching that is needed in operational individual-tree-based growth estimation in areas with narrow trees. The method is based on minimising the distances between tree tops in an N-dimensional data space. The experiments showed that the location of trees (derived from laser data) and height of the trees were together adequate to provide reliable tree-to-tree matching. In future, the crown area should also be included in the matching as the fourth dimension.

In Yu *et al.* (2007), high-density multi-temporal laser scanner datasets acquired at different dates between 1998 and 2003 were used to estimate the tree mean height and volume growth at plot level in a boreal forest. Laser datasets were collected with a TopoSys laser scanner in 1998, 2000 and 2003, with a nominal point density on the target of 10 points per m^2. Three techniques were used to predict the growth values, i.e. a method based on individual tree top differencing, digital surface model differencing and canopy height distribution differencing. The lidar-estimated results of stand parameters were regressed against the corresponding values derived from field measurements of tree height and diameter at breast height. The best results were obtained for mean height growth (R^2 value of 0.86 and standard deviation of 0.15 m) using the individual tree top differencing method. The best results for volume growth were an R^2 value of 0.59 and a standard deviation of 8.39 $m^3 ha^{-1}$ (35.7%) using DSM differencing. Combined use of the three techniques in a linear regression analysis yielded a better result for volume growth estimation (R^2 value of 0.77), but did not improve the estimation for mean height growth. The results indicated that it is possible to determine forest mean height and volume growth with an acceptable accuracy using multi-temporal laser scanning.

Laser data can also be used for change detection. Yu *et al.* (2003, 2004a) also examined the applicability of airborne laser scanners in monitoring harvested trees, using datasets with a point density of about 10 points per m^2 over a 2 year period. Out of 83 field-checked harvested trees, 61 were detected automatically and correctly. All the mature harvested trees were detected; it was mainly the smaller trees that were not. As proposed by Yu *et al.* (2004a and 2005), individual-tree-based inventories and repeated airborne laser scanning should prove to be effective data collecting techniques, especially for strip-based sampling, and in future forest and carbon sink inventories, where permanent sample plots are placed across a country. The proposed laser methods may be used to replace a large number of permanent plots with laser scanning techniques or increase the number of plots that can be collected. 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.

7. Intensity and waveform

The use of intensity of the laser beam in forest parameter estimation has, to date, been limited to tree species classification (Holmgren and Persson 2004) or for matching aerial imagery and laser scanner data. Use of intensity data, however, is complicated because intensity depends on a variety of factors affecting reflected laser signal from a surface including: range, incidence angle, bidirectional reflectance function effects (BRF), atmospheric transmittance and attenuation, transmitted power and beam divergence. More effective use of intensity values can be made if these factors are compensated for.

Ahokas *et al.* (2006) showed the feasibility of portable brightness targets for the calibration of airborne laser scanner intensity from different flying altitudes, namely 200, 1000 and 3000 m. A high coefficient of correlation, R^2, value (between mean intensity for each reflectance value and scaled intensity) confirmed the use of the applied calibration targets for intensity calibration. It was further shown that the intensity values need to be corrected with respect to: (1) range, (2) incidence angle (both BRF and range correction), (3) atmospheric transmittance, (4) attenuation using dark object addition, and (5) transmitted power (difference in PRF will lead to different transmitter power values). After these corrections, the intensity values were directly relative to target reflectance from all altitudes and could be used as calibrated values in classification. Ahokas *et al.* (2006) recommended that this kind of correction or calibration of the intensity values should be carried out in the pre-processing part of the data in order to increase the usability of the intensity information. At present, work is on-going in the use of calibrated intensity as part of the classification and the use of intensity to produce stereoimaging under dark conditions.

A full review of waveform laser applications in forest inventory is beyond the scope of this paper, but it is interesting to highlight a few recent studies. In Drake *et al.* (2002), several statistical predictors, such as lidar canopy height, height of median energy, and ground return ration, using waveform information are depicted. According to Wagner *et al.* (2004) the use of full-waveform in airborne laser scanner gives an opportunity to classify the point cloud based on the shape of the echo. Another important advantage proposed by Wagner *et al.* (2004) is that the detection of the trigger pulses can be applied after data capturing to improve DTM generation for example. Persson *et al.* (2005) reported that the number of additional points that could be extracted using the waveform signal ranged between 18% and 57%, depending on the type of vegetation. They proposed that additional points can give a better description of the vertical structure of vegetation and can possibly improve tree species classification. Similarly, Reitberger *et al.* (2006) described an approach to tree species classification based on features that are derived by a waveform decomposition of full waveform lidar data. Point distributions were computed in sample tree areas and compared with the numbers that result from a conventional signal detection. The examples show clearly that the number of 3D points measured was much larger than the number of 3D points measured by conventional first and last pulse techniques. Unsupervised tree species classification was carried out using special tree saliencies derived from the lidar points. The classification into two clusters (deciduous, coniferous) led to an overall accuracy of 80% in a leaf-on situation. It is expected that the waveform-based techniques of the small-footprint ALS will develop significantly in the coming years.

8. Recommendations

Extraction of the DTM for forested areas can be considered to be well established. However, more research is needed in the following areas. Since the errors accepted in tree height are greater than those possible for a DTM with the ALS, the automation of DTM derivation in forest areas should be improved. There should be development of more automatic strip adjustment tools (the fitting of near-by laser strips to reduce geometrical errors in the data) and development of DTM tools in high-relief terrain. High-relief terrain is challenging for forest applications. The quality of DTM using large scanning angles and high flight altitudes (>3 km) is still an unresolved question. The ability to use wider scan angle data increases the efficiency of the mapping process due to requirements for less flight lines. Thus, high altitudes and large scanning angles are attractive solutions. Because of improvements in sensor technology, including new waveform recording, further work on the development of the DTM algorithms and analysis of the quality of the new systems are also required.

The quality of the CHM has proved to be high. With relatively dense point clouds, the height values given for individual trees are about as accurate as conventional hypsometric measurements. The following research is proposed. The cause, or causes, of the underestimation of tree height even when the laser footprint is hitting the top of a tree crown needs to be determined. This is not simple as a number of factors need to be isolated and considered. These include: the amount and height of ground vegetation; the algorithm used to calculate the digital terrain model; the power and sensitivity of the laser system; the signal processing and thresholding algorithms used to trigger a first return; the quantity, geometry and type of vegetation it takes to trigger a first return; the pulse penetration into trees; and the tree shape and species. This should be understood in general and for each sensor type and signal processing system. It is proposed that a cost-effective method of calibrating the underestimation of the laser-derived tree height needs to be developed. The key factors are: the number of plots or trees needed to successfully calibrate the underestimation; for how many forest or tree types and configurations does a different calibration have to be developed; and how does one stratify the area being surveyed in order to apply different calibrations.

The methods for individual tree isolation using laser scanner data are still under development and empirical studies on the quality of the approaches are needed. This is currently being carried out in the ISPRS/EuroSDR Tree Extraction comparison coordinated by the Finnish Geodetic Institute. On the basis of that experience, it is thought that it will be possible to improve the retrieval of individual tree characteristics, especially the detection of the tree locations and segmentation of crown outlines. Preliminary results indicate that forest conditions play an important role in the determination of the accuracy of the methods, and thus, the accuracy obtained with each method could not be anticipated from the previous literature.

One possible future inventory technique is to combine low-density laser data over large areas (density obtained with highest possible flight altitude and highest possible incidence angle) with low-altitude high-density laser cross-strips (pulse density >3 points per m^2). The high-density strips are used for strip adjustment, analysis of the quality of the DTM and CHM of the low-density data and also for ITC isolations. The large area covered with low-density data can then be calibrated with the ITC information from the high-density part. With multi-temporal surveys conducted over high-density strips, it is possible to analyse the growth of the forests statistically in the region. Alternatively, the high-density strips can be performed with high-resolution digital aerial imagery and the ITC approach.

The intensity would be a more attractive predictor if there were several simultaneous wavelengths. In the future, we will see multiple wavelength systems that will allow improved automatic classification of forest types and species. The use of the waveform should be more than that of increasing the number of returns detected. Most probably, the adaptation of waveforms in forestry will lead to the significant improvement of the distribution-based techniques.

There are several ways to improve growth estimates. In studies carried out by Yu *et al.* (2004, 2005, 2006, 2007), volume change 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, diameter at breast height), 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.

Seamless integration with optical data is important for widespread use, both due to the synergy of data for forest information and for efficiency and cost of data acquisition. Multiple use of the data is currently beneficial and important for implementing applications. For example, forest companies using the terrain data to design roads and save construction costs and also using the data for forest inventory.

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