EXPERIENCES AND POSSIBILITIES OF ALS BASED FOREST INVENTORY IN FINLAND

Maltamo, M.[a], Packalén, P. [a], Peuhkurinen, J.[a], Suvanto, A. [a], Pesonen, A.[a] & Hyyppä, J.[b]

a) University of Joensuu, Faculty of Forest Sciences, P.O. Box 111, FI-80101 Joensuu, Finland. Tel.+358 13 2513615. E-mail: matti.maltamo@joensuu.fi, petteri.packalen@joensuu.fi, jussi.peuhkurinen@joensuu.fi, aki.suvanto@joensuu.fi, annukka.pesonen@joensuu.fi

b) Finnish Geodetic Institute, Geodeetinrinne 2, P.O. Box 15, FI-02431 Masala, Finland, E-mail: juha.hyyppa@fgi.fi

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ABSTRACT

During last ten years the research concerning airborne laser scanning based forest inventory applications has been very active in different parts of the world. In Finland, both basic approaches, single tree detection and area based modeling have been widely examined. In the following the results of the ALS based forest inventory experiments and further possibilities in Finland are reviewed and discussed. A short review of Finnish forestry in relation to possibilities of ALS based forest inventories is included as well. Finally, some examples concerning the comparison of single tree detection and area based modeling and the usability of spatial information provided by ALS data are presented.

1. INTRODUCTION

During last ten years the research concerning airborne laser scanning (ALS) based forest inventory applications has been very active in different parts of the world (e.g. Næsset, 1997; Magnussen & Boudewyn, 1998; Hyyppä et al., 2001; Persson et al., 2002; McCombs et al., 2003; Takahashi et al., 2005; Tickle et al., 2006; Koch et al., 2006). Most of the studies have been conducted by using discrete return small footprint systems but there are also large footprint lidar applications as well (Drake et al., 2002).

In Finland, both basic approaches to utilize ALS data, single tree detection (Hyyppä & Inkinen, 1999; Hyyppä et al, 2001; Maltamo et al., 2004a; Yu et al., 2006; Korpela, 2007; Peuhkurinen et al., 2007) and area based modeling (Suvanto et al., 2005; Maltamo et al., 2006a; c; Packalen & Maltamo, 2007) have been examined. In the following, the results of the ALS based forest inventory experiments and further possibilities in Finland are reviewed and discussed. Forest inventories are usually multipurpose but here we concentrate mainly on prediction methods of living tree stock. Some examples concerning the comparison of single tree detection and area based modeling as well as spatial information provided by ALS data are also presented. However, to understand the growing conditions and forest inventory traditions in Finland a short review of Finnish forestry in relation to possibilities of ALS based forest inventories is also included.

2. FOREST INVENTORIES IN FINLAND

The forests of Finland are located in boreal vegetation zone. The number of existing tree species is rather low, including coniferous pine (Scots pine [*Pinus sylvestris L.*]) and spruce species (Norway spruce [*Picea abies L. karst*]), and as deciduous birches (Silver birch [*Betula pendula Roth*], downy birch [*Betula pubescens Ehrh.*]), alders (grey alder [*Alnus incana*], red alder [*Alnus glutinosa*]) and aspen (European aspen [*Populus tremula*]) species. At stand level, most of the forests are dominated either by pine or spruce. There is no pure plantation forestry in Finland. Although considerable proportion of regenerated stands have been planted by one tree species the rotation age is so long that other species usually naturally regenerate to stand. As a result, a considerable proportion of stands are mixed at least in some level. Only the least fertile stands, usually located in northern Finland consist of pine only. Of course, silvicultural treatments may also favour certain tree species. One specific phenomenon in boreal forests is also high stand density by means of number of stems whereas trees are rather small. For example, in managed forests of Matalansalo test area, used in several ALS studies, the average stand density is about 1500 stems per hectare and in mature stand strata still over 1250 stems per hectare (Suvanto et al., 2005). As a comparison, in the study data by Heurich and Weinacker (2004) the stand density in southeastern Germany on temperate forests was on average 540 stems per hectare.

In Finland forest inventory is carried out on two levels: National forest inventory (NFI) and forest management planning. NFI is based on systematic cluster sampling of field plots and covers whole country (Tomppo, 2006a). This data is used for calculation of national and regional forest resources and for national level planning. In addition, satellite images are used in the multi-source National Inventory as an auxiliary material (Tomppo, 2006b).

ALS data based sample plots is not a realistic alternative for replacing field measured NFI sample plots. This is due to the fact that one of the main requirements of NFI is that forest resource results should be unbiased and this cannot be quaranteed by using ALS data. Furthermore, information concerning tree stock is only a minor part of the measurements in these plots. Some other data needs consist e.g. of forest health, biodiversity and forest soil variables and most of these cannot be remote sensed (the head of the NFI of Finland, Dr. Kari T. Korhonen, personal comm.). On the other hand, large scale ALS data such as National Laser Scanning (e.g. Artuso et al., 2003) could provide auxiliary information for multi-source inventory in the form of digital terrain model (DTM), canopy height model (CHM) or stand characteristics interpretation on systematic grid.

Forest management planning in private forests is usually based on information collected by forest compartments (stands) (Poso, 1983). A conventional inventory by compartment includes expensive field work, but the number of assessments per stand is typically small, resulting in low precision of estimated stand variables. All assessments are made on tree species level already in the field and as a final product tree species specific timber sortiments are calculated. The accuracy of prediction of stand total volume achieved in compartment inventory usually varies between 15 and 30% (Haara & Korhonen, 2004). For tree species the results are even considerably worse. In fact, during recent years, the costs and accuracy of conventional field work based small area forest inventories have been at unsatisfactory levels (e.g., Kangas & Maltamo, 2002). There is, therefore, an increasing pressure to improve methods of carrying out field inventories in small areas. The main approaches to developing a compartment inventory have been the modification of field measurements and the application of remote sensing methods to support, or even replace, field measurements. For the purpose of replacing current inventory, ALS based methods have a very high potential.

Other forest inventory applications in Finland include specific inventories for detailed purposes, such as wood procurement planning or forest protection survey. These inventories should produce very fine grained information of variables of interest. In addition, the area they cover can vary from one marked stand to large scale level. The usability of ALS data in these inventories varies. For wood procurement planning ALS based methods could provide detailed information but due to the small area of target stands the cost efficiency of data may not be sufficient. Concerning characteristics of forest protection, some of them may be mapped by ALS data and the others may be almost impossible to recognise. In general, ecological information can be obtained from ALS data (Hill et al., 2003; Hashimoto et al., 2004)

All in all the characteristics of Finnish forests (low number of tree species but usually more than one in stand, high stand density, no fast growing plantations) and inventory output needed (stand variables by tree species) define the possibilities for ALS data to be applied. These possibilities are further discussed later in this paper.

3. ALS EXPERIENCES OF FOREST INVENTORY IN FINLAND

3.1 General

The first ALS based forest inventory studies in Finland were based on single tree detection and high pulse density data (Hyyppä & Inkinen, 1999; Hyyppä et al., 2001). In fact, Hyyppä and Inkinen (1999) were among the first ones to apply single tree detection with ALS data. The accuracy was found to be superior already in these first studies the standard error (without bias) being about 10% for stand volume. In the studies by Hyyppä and Inkinen (1999) and Maltamo et al. (2004b) the proportion of detected trees was only about 40%. This was due to the multilayered and unmanaged stand structure of the study area. Detailed information concerning ALS studies in Finland before 2004 can be found from review by Hyyppä et al. 2003. More recent developments in Nordic countries and in boreal forests in general have been reported e.g., by Næsset et al. (2006) and Hyyppä et al (2007). In Finland, there has also been active research going on concerning the quality of DTM construction in forested areas (e.g. Hyyppä et al., 2005; Korpela & Välimäki, 2007). In addition, the TerraScan software (by Arttu Soininen) from Terrasolid Oy is assumed to be the global market leading software concerning laser scanning processing.

3.2 Single tree detection

More recently the research of single tree approach has concentrated on detection algorithms, recovery of undetected trees, height growth and change detection. In addition, crown height estimation and, especially, tree species recognition are under growing research interest in Finland.

Concerning detection algorithms one problem on raster canopy height models is handling of tree crowns of different sizes. On laser scanner data one size attribute, height, is directly available. This gives possibilities to develop processing methods that adapt to the object size. In the study by Pitkänen et al. (2004) three adaptive methods were developed and tested for individual tree detection on CHM. In the first method, the CHM was smoothed with canopy height based selection of degree of smoothing and local maxima on the smoothed CHM were considered as tree locations. In the second and third methods, crown diameter predicted from tree height was utilised. The second method used elimination of candidate tree locations based on the predicted crown diameter and distance and valley depth between two locations studied. The third method was modified from scale-space method used for blob detection. Instead of automatic scale selection of the scale-space method, the scale for Laplacian filtering, used in blob detection, was determined according to the predicted crown diameter.

Possibility to characterize suppressed trees that cannot be detected has also been of interest. Maltamo et al. (2004a) combined theoretical distribution functions and laser scanning data to describe small and suppressed trees, which tree crown segmentation methods was not able to detect. The use of original point clouds instead of digital surface models (DSM) or CHMs also gives possibilities for detection of small trees. Since, some of the laser pulses will penetrate under the dominant tree layer, it is also possible to analyze multilayered stands. In Maltamo et al. (2005), the existence and number of suppressed trees was examined. The results showed that multilayered 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.

Correspondingly, Mehtätalo (2006) used theoretical approach to describe small trees. The probability of a tree being observed was related to its height and was equal to the proportion of the forest area not covered by taller trees. Mehtätalo (2006) presented mathematical formula which was based on the following assumptions: (i) trees are randomly located within the stand and crown diameters within a stand are uncorrelated, (ii) tree height increases as a function of crown diameter, (iii) the tree crown forms a circle around the tree tip, and (iv) a tree is invisible if the tree tip locates within the crown of a taller tree. Furthermore, different approaches were proposed for the correction of the censoring effect upon the observed distribution of crown areas. The used approach provided theoretically accurate estimates for the distribution of crown areas and the number of stems.

Yu et al. (2004) demonstrated the applicability of airborne laser scanners in estimating height growth and monitoring fallen or cut trees. Out of 83 field-checked fallen or cut trees, 61 were detected automatically and correctly. All the mature cut trees were detected; it was mainly the smaller trees that were not. Height growth was demonstrated at plot and stand levels using an object-oriented tree-to-tree matching algorithm and statistical analysis. In Yu et al. (2006) the potential of measuring individual tree height growth of Scots pine in boreal forest was analysed. Three different types of variables were extracted from the point clouds representing each tree: (i) the difference of highest z value, (ii) difference between DSMs of tree tops and, (iii) difference of 85, 90 and 95% quartiles of the height histograms corresponding to a crown. The results indicate that it is possible to measure the height growth of an individual tree with multi-temporal laser surveys.

Maltamo et al. (2006b) compared the results of the prediction of crown height characteristics using ALS data and intensive field measurements. Crown height models were constructed both at the tree and plot level for Scots pine, Norway spruce and birches. The ALS based models included independent variables of tree levels, such as tree height, crown area and independent plot-level variables, i.e. canopy height and density quantiles and proportion of vegetation hits. The results indicated that the ALS-based crown height models were more accurate than the field-measurement-based models when plot-level information was used as independent variables. However, the field-measurement-based tree-level models for Scots pine and Norway spruce were more accurate than the ALS-based models. Even so, the accuracy of the different models was very similar.

Related to wood procurement planning Peuhkurinen et al. (2007) applied ALS data and field measurements to characterize timber sortiments of two pure Norway spruce marked stands. Pre-harvest measurement was realized by using different methods as follows: (i) lidar-based individual tree detection (see Pitkänen et al., 2004) and local constructed dbh model (tree height as predictor), (ii) lidar-based individual tree detection and existing regional dbh model for spruce presented by Kalliovirta and Tokola (2005), (iii) lidar-based individual tree detection and existing regional dbh model (both tree height and maximum crown diameter as predictors), (iv) systematic field plot sampling data, (v) field inventory by compartments and, (vi) area based canopy height distribution approach. The mean stand variables were predicted with the models presented by Suvanto et al. (2005). As a ground truth data harvester measurements were used and the comparison of the methods was based on bucking simulations.

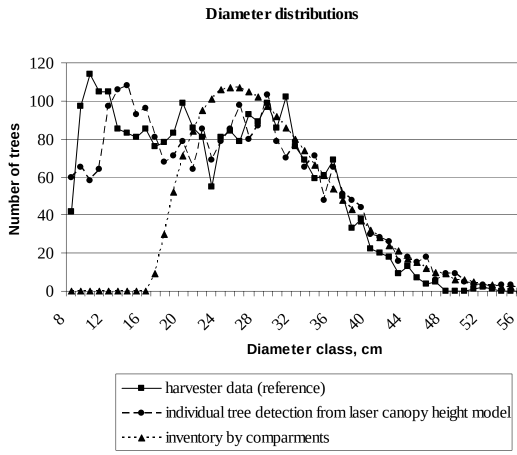

Fig. 1. Comparison of diameter distributions of single tree detection, compartment inventory and harvester reference data in a marked stand (Peuhkurinen et al. 2007).

The results of Peuhkurinen et al. (2007) illustrated considerable advantage of lidar-based single tree detection procedure compared to other studied methods in producing pre-harvest measurement information. Single tree detection with local dbh model (method (i)) was the most accurate method by means of error index of diameter distribution (Reynolds et al., 1988), saw wood and pulp wood volumes and apportionment indexes used in relation with distribution of logs. In fact, single tree detection found 2561 trees whereas harvester data included 2638 trees, corresponding figures for saw wood volumes were 1262 m^3 and 1267 m^3, respectively. Predicted tree diameters were even able to produce bi-modal shape of diameter distribution (Fig. 1). Though, it must be noticed that the study by Peuhkurinen et al. (2007) was done using two marked stands only and, thus, has the nature of a case study.

Pyysalo (2006) developed 3D vector models of single trees from ALS data in order to derive geometry features. The vector model construction included four stages: (i) laser point classification, (ii) DTM construction, (iii) extraction of points from each individual tree and, (iv) vector model creation. The extracted features were tree height, crown height, trunk location, and crown profile. According to the derived results tree shape is underestimated in vector models in both vertical and horizontal direction Tree location were extracted with an accuracy of 2 m and tree heights with an accuracy of 1.5 m (Pyysalo, 2006).

Säynäjoki (2007) examined tree species classification between aspen and other deciduous trees by using single tree recognition of ALS data. Watershed segmentation was used to create crown segments on the smoothed CHM (Pitkänen et al., 2004). Crown segments of deciduous trees were used to classify trees to aspen or other deciduous trees using linear discriminant analysis. Classification accuracy between aspen and other deciduous trees was as its best 79.1%. Predictors in this classification function were proportion of vegetation hits, standard deviation of pulse heights, accumulated intensity on 90^{th} percentile and relation of proportions of laser points reflected on 95^{th} and 40^{th} height percentiles. In addition to the study by Säynäjoki (2007) there is a lot of research interest going on in Finland to recognise tree species from single tree detected ALS data. In Liang et al. (2007), it was shown that the difference between first and last pulse is a valuable feature for trees species classification. It gives reliable (89%

accuracy) classification between coniferous and deciduous trees under leaf-off conditions.

Finally, international EuroSDR/ISPRS Tree Extraction project is coordinated by Finland (Hyyppä & Kaartinen 2006). The project includes twelve partners and the study area is located in southern Finland. The aims of the project are: (i) to compare different algorithms in tree extraction, (ii) to study the effect of pulse density and (iii) to improve results by combining ALS data and aerial images. The characteristics to be compared are tree and tree species detection and tree height estimation. The results clearly showed that the variability of tree location accuracy is small as a function of pulse density and it mainly changes as a function of the provider. With the best models for all the trees, the mean location error was less than 1 m and the difference with 2, 4 and 8 pulses per m^2 was negligible. With trees over 20 m, the accuracy of tree location of 0.5 m was obtained. Tree height quality analysis using selected 70 reference trees, the reference height was known with accuracy of 10 cm, showed again that the variability of the pulse density was negligible compared to method variability. With best models RMSE of 50 to 80 cm was obtained for tree height. Even the 2 pulses per m^2 seemed to be feasible for individual tree detection. Percentage of the found trees by partners showed that the best algorithms found 90% of those trees that were found at least by one of the partners. There was again higher variation with the method used rather than pulse density. The results of the test showed that the methods of individual tree detection vary significantly and that the method itself is more significant for individual tree based inventories rather than the applied pulse density (Harri Kaartinen and Juha Hyyppä, personal comm.).

3.3 Area based modelling

Research concerning area based modelling by using canopy height distribution approach and low pulse density ALS data started year 2004 in Finland (Suvanto et al., 2005; Maltamo et al., 2006a). First studies confirmed the corresponding accuracy observed in other Nordic countries (e.g. Næsset, 2002; 2004; Holmgren, 2004; Næsset et al., 2004). Juntunen (2006) also made cost plus loss comparisons between ALS based stand variables and characteristics of conventional inventory by compartments (see e.g., Eid et al., 2004). When compared to optical sensors canopy height distribution approach was found to be more suitable alternative for the next generation method for compartment inventory in Finland (Uuttera et al., 2006). Instead of using regression models in construction of stand variable models k-MSN model was used by Maltamo et al. (2006c). The k-MSN method is a non-parametric method, which uses canonical correlation analysis to produce a weighting matrix used in the selection of k Most Similar Neighbors from reference data. Most Similar Neighbors are observations that according to predictor variables are similar to the target of prediction. When using k-MSN model the accuracy of stand volume was improved when compared to regression models (Maltamo et al., 2006). Additional information of aerial photographs or stand register data further slightly improved the accuracy.

When constructing area based forest inventory application a ground truth sample of accurately measured field plots is needed. One possibility for reducing the costs lies in the use of existing field plots for ground truth purposes. The most obvious alternative in Finland is to use truncated angle count sample plots of the National Forest Inventory. Due to the lack of suitable angle count ground truth data and corresponding laser data, Maltamo et al. (2007a) tested this possibility using data on fixed area sample plots, in which tree locations were simulated. The trees for a truncated angle count sample plot were then chosen and the resulting data together with the characteristics of an ALS -based canopy height distribution were used to construct regression models to predict stem volume, basal area, stem number, basal area median diameter and the height. The accuracy of the stand attributes was found to be almost as good as in the case of models of fixed area plots. However, one drawback of this study was that there were no field plots which were located on stand edge. Such plots are typical for systematic sampling based forest inventory applications, such as NFI of Finland.

Närhi (2007) tested the usability of area based canopy height distribution approach to define the need and timing of silvicultural treatment on Norway spruce sapling stands. Two approaches were used: (i) ALS characteristics were directly used to classify sapling stands according to treatment need by using discriminant analysis and, (ii) regression models were constructed for mean height and stand density correspondingly as Næsset and Bjerknes (2001). After that, the need and timing of silvicultural treatment was classified according to these predicted characteristics. The results indicated that overall accuracy of about 70% was achieved in classification. The stands where there is a need for treatment were found more accurately than those who did not have need for that.

Basicly, area based canopy height distribution approach produces stand variables, usually stand volume, stem number, basal area, basal area median diameter and tree height. However, ALS data can also be used to predict parameters of a theoretical diameter distribution model of a stand (Gobakken & Næsset, 2004; 2005). In Finland, Maltamo et al. (2006a) compared prediction of diameter percentiles and the use of predicted stand characteristics to further predict Weibull parameters. More flexible and local percentile based distribution was able to better describe diameter distribution of heterogeneous stands.

In Maltamo et al. (2007b) the accuracy of ALS-based stem frequency and basal area diameter distribution models by using Weibull distribution were compared. Furthermore, the usability of calibration estimation (see, e.g., Kangas & Maltamo, 2002) to adjust the predicted distributions to be compatible with the ALS based estimated stand volume was presented. As a main result, the authors state that when diameter distributions are predicted using ALS data, basal area diameter distributions may not be needed. This represents a considerable improvement in the inventory system, since basal area is not in itself an interesting end-product variable. When stem frequency distributions are directly usable, this would provide a more realistic description of the stand structure and generate simulations for the further development of the tree stock.

Pesonen et al. (2007) analysed the potential of ALS data for estimating coarse wood debris (CWD) volumes in conservation area of the Koli National Park. The accuracy of the ALS data proved adequate for predicting the downed dead wood volume (RMSE 51.6%), whereas the standing dead wood volume estimates were somewhat poorer (RMSE 78.8%). The downed dead wood volume estimates were found to be substantially more accurate than traditional predictions based on field measurements. Correspondingly, Kotamaa (2007) analysed the potential of ALS data for estimating downed dead wood volumes in managed forests in Juuka, eastern Finland. The accuracy was found to be considerably worse. However, ALS data was able to satisfactory classify plots whether they included downed dead wood or not.

In all abovementioned studies (excluding Säynäjoki, 2007 and Liang et al., 2007) tree species have been ignored and total tree stock has been considered. However, species-specific stand characteristics are essential in Finland. To solve this problem Packalén and Maltamo (2006) combined information from ALS data with digital aerial photographs to predict stand volume by tree species. Furthermore, Packalén and Maltamo (2006; 2007) applied the non-parametric k-MSN method to predict species-specific forest variables volume, stem number, basal area, basal area median diameter and tree height simultaneously for Scots pine, Norway spruce and deciduous trees as well as total characteristics as sums of the species-specific estimates. The combination of ALS data and aerial photographs was used in these studies. The predictor variables derived from the ALS data were based on the height distribution of vegetation hits, whereas spectral values and texture features were employed in the case of the aerial photographs. The results showed that this approach can be used to predict species-specific forest variables at least as accurately as from the current stand-level field inventory for Finland.

4. CALCULATION EXPERIMENTS

4.1 Comparison of single tree detection and canopy height distribution approaches

Area based canopy height distribution and single tree based approaches to utilise ALS data have been compared and discussed in some reviews (Næsset et al., 2004; Hyyppä et al., 2007). However, reliability figures presented earlier have been based on different reliability characteristics and study areas as well. Peuhkurinen et al. (2007) observed the better accuracy of single tree detection in pre harvest measurement case study. The example stand had rather low stand density (465 stems per hectare). However, for forest inventory purposes, comprehensive forest resource estimate should be provided in relation to area to be considered, not just for mature stands.

In this paper we theoretically compare these two approaches in Matalansalo test area. This area has been earlier used in several ALS studies (Suvanto et al., 2005; Maltamo et al., 2006c; 2007a; b; Packalén & Maltamo, 2006; 2007). The total size of the area is about 1200 hectares. There are a total of 472 field sample plots (radius 9 meters) located in the area and ALS campaign was conducted in summer 2004 using an Optech ALTM 1233 laser scanning system operating at an altitude of 1500 m above ground level. Sampling density of the data was about 0.7 measurements per one square metre. The pulse density does not allow individual tree detection and, therefore, we simulated single tree approach as follows: (i) it was expected that all trees were found, i.e. true tee heights of all field measured trees were used, (ii) tree species recognition produced 100% accuracy, i.e., tree species recorded for each field measured tree was used and, (iii) tree diameter was predicted with the help of tree height (*h*) either by using existing, i.e. no calibration, regional regression models by Kalliovirta and Tokola (2005) or from sample tree material, i.e. calibrated by using about 1200 measurements, constructed local tree diameter models. The model forms were for Scots pine $\sqrt{dbh} = f(\sqrt{h})$ and for Norway spruce and deciduous tree species $\sqrt{dbh} = f(h)$. After that we calculated stand volumes by using volume functions of Laasasenaho (1982). As a result RMSE's of 25.3% and 22.9% for plot level volumes were obtained for regional and local models, respectively. When compared these figures to canopy height distribution approach based estimates of regression models 19.9% (Suvanto et al., 2005), k-MSN estimate 15.6% (Maltamo et al., 2006c), species-specific k-MSN estimates summed to plot level 20.5% (Packalén & Maltamo, 2007) and diameter distribution based plot volume estimate 20.6% (Maltamo et al., 2007b) it can be seen that the accuracy is slight worse although it was expected that tree and tree species detection totally succeeded. This is due to the fact that the relationship between tree height and diameter is far from deterministic. Allometric relationship between tree diameter and height defines only certain limits for the variation of these to variables, but characteristics such as stand density, stand silvicultural history, genetic factors of tree seed, tree position in a stand, site fertility, height above sea level, distance from sea, mineral soil/peatland and stand development class effect considerably to this relationship

In real world applications all trees and tree species would not be detected, tree groups would cause some problems and tree heights would be underestimates (e.g. Maltamo et al., 2004b), but, the errors obtained here might not be increased considerably due to the correlations between different errors (Kangas, 1999). On the other hand, our simulation was not able to take into consideration other variables produced by single tree detection, usually tree crown area or diameter (Hyyppä et al., 2001; Persson et al., 2002; Maltamo et al., 2004a). In the study by Kalliovirta and Tokola (2005) the increase in accuracy when maximum width of tree crown was added to dbh/h model was 2.5 %-units in tree diameter prediction. Furthermore, in Finnish conditions the effect of tree crown area or diameter to increase accuracy of volume prediction has been found to be 5-7 %-units (Maltamo et al., 2004a; Villikka et al., 2007). Furthermore, the use of height and density distributions of 3D point cloud of each detected tree would additionally slightly improve the accuracy as suggested by Villikka et al. (2007). Also some of the characteristics mentioned in previous paragraph could be used in dbh/h models or in the stratification of the data.

In fact, it is obvious in statistical manner that if the target variable is stand volume, direct prediction model, as in the case of canopy height distribution, is the most accurate alternative to predict it. To further compare these two approaches by using diameter distribution estimates we also calculated error index presented by Reynolds et al. (1988):

$$e = \sum_{i=1}^{K} \left| \hat{f}_i - f_i \right| \tag{1}$$

where $\hat{f}_i$ and f_i are the predicted and true frequency of diameter class *i*, respectively, and *K* is the number of diameter classes. The error index was calculated in 1-cm-diameter classes for stem numbers at the plot level. Thus, the error index of a given plot was the sum of the absolute differences between the actual and predicted stem frequencies of the diameter classes. Diameter distribution estimate was in the case of canopy height distribution approach based on Weibull distribution (Maltamo et al., 2007b). Correspondingly, diameter estimates of local diameter models were used in the case of single tree detection. Tree species recognition was not used in these comparisons, i.e. distributions described tree total stock. As a result, the average values of error indexes were 30.1 for Weibull distribution based estimates and 30.8 for single tree detection. In 239 plots Weibull distribution was more accurate and in 211 plots single tree detection, in the rest (n= 22) these methods were as accurate by means of Reynold's error index.

Finally, RMSE figures for volumes of saw wood sized trees (dbh>17 cm) were calculated. This characteristic approximates saw wood proportion, an important variable when deriving value or final cut decision of the stand. In the case of Weibull distribution the RMSE was 32.2% and for detected single trees, which diameters were predicted with local tree diameter models, the RMSE was 40.3%.

At least when only tree height is used to predict tree diameter single tree detection is not able to produce more accurate common forest resource estimates than area based methods. This is true for the stand volume as well as derived diameter distribution or certain detailed part of tree stock. Single tree detection does directly measure physical dimension of a tree but tree height in itself is not an interesting variable in most of the forest inventory applications. When considering biodiversity aspects or certain habitat requirements stand vertical structure is of primary interest but usually diameter distribution and end products derived from it together with tree height and tree species information are most important output variables of forest inventory.

The accuracy of single tree detection could be improved by calibrating tree diameter estimates at stand level. This would, however, need field visit and measurement of GPS mapped tree(s) and their height/diameter -relationship almost in each target stand, i.e. extensive and very expensive reference data for calibration is needed. Alternatively, single tree detection based estimates, such as number of trees and stand volume, could also be calibrated by using corresponding area based ALS estimates. For general forest resource information field calibration would not be cost-efficient, since such field visits could take as much time as current compartment inventory in Finland (on average 10 minutes per stand). Without calibration there is, however, a high possibility of large errors in operational inventories. For certain purposes, such as pre harvest measurement of a marked stand in Finland single tree detection could still be very interesting alternative expecting that tree and tree species detection algorithms are highly successful.

4.2 Usability of spatial information provided by ALS data

Both basic approaches to process ALS data for forest information purposes also include some spatial information which has not yet been utilised as much as possible. In the case of single tree detection location and height of each detected trees are obtained as well as same characteristics of neighbouring trees. This allows us to calculate height based competition indexes. In the following we calculate additive competition index based on elevation angle sums (see Miina & Pukkala, 2000):

$$CI = \sum_{i=1}^{n} a\tan\left(\frac{(h_{neighbour} - 0.8 * h)}{dist}\right) \qquad (2)$$

where $h_{neighbour}$ is height of neighbour tree, n is number of neighbouring trees and *dist* is distance between target and neighbour trees, maximum distance of 8 meters was taken into consideration in the calculations.

This index was calculated for trees of two pine dominated mapped field sample plots and corresponding individual tree recognised ALS data including point density of 3.88 pulses per square meter. ALS data was acquired in summer 2005 using an Optech ALTM 3100 scanner operating at a mean altitude of 900 m above ground level. Example sample plots were located on Koli National park and algorithms of Pitkänen et al. (2004) were used for tree detection. Tree coordinates and heights were needed in the calculations.

In the case of sparse density sample plot almost all trees were detected and distributions CI-indexes were quite close to each other (Fig. 2). All in all, ALS data was capable of producing realistic estimates of competition indexes. On the other hand, in dense sample plot less than 50% of trees were detected and ALS data based CI estimates are not realistic (Fig. 3). In the case of small trees there are only a few ALS detected trees and also for larger trees underestimates are obtained since there are too few neighbouring trees taken into consideration in these estimates.

Further use of spatial indexes lies, e.g., in situation where tree level distance dependent growth models are constructed (e.g. Miina & Pukkala, 2000). Additional information that ALS data could provide for such models would be spatial indexes as described here, past height growth estimates from multitemporal ALS data either at single tree level or plot level as suggested by Yu et al. (2004, 2006) and information included in laser based DTM, e.g. slope. Field measurements including at least time series of two measurements are, of course, needed for model construction, but when applying such models a considerable amount of independent variable information could come from ALS data.

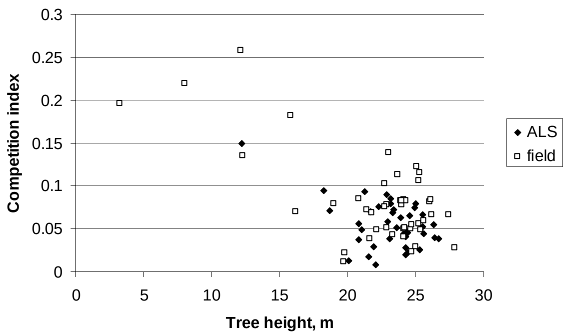

Fig. 2. An example plot of spatial competition indexes calculated from field measurements (n=44) and ALS detected trees (n=39). Stand variables: basal area=24.5 m^2ha^{-1}, mean height=24.7 m and number of stems = 489 per hectare.

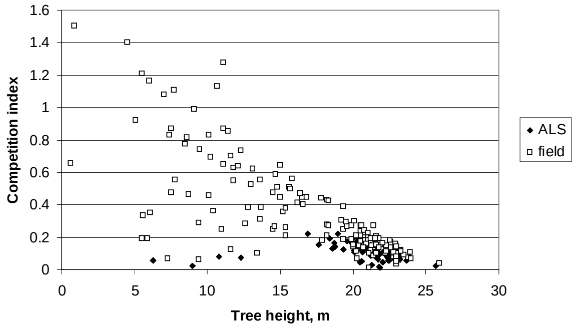

Fig. 3. An example plot of spatial competition indexes calculated from field measurements (n=151) and ALS detected trees (n=67). Stand variables: basal area=31.7 m^2ha^{-1}, mean height= 24 m and number of stems= 1677 per hectare

In the case of canopy height distribution approach spatial information can be considered by using within stand information provided by ALS based grid cells. In our example two stands in Juuka test area are used. ALS data were collected during summer 2005 using an Optech ALTM 3100 scanner operating at an altitude of 2000 m above ground level resulting point density of about 0.6 pulses per square meter. Field ground truth consists of systematic sample (30 m distance) of angle count sample plots measured originally for stand delineation purposes (Mr. Jukka Mustonen, personal comm.). ALS based stand variable estimation was based on the principle presented by Packalén and Maltamo (2007). The size of the systematic grid cell was 16 m * 16 m which was close to original field sample plot (radius 9 m).

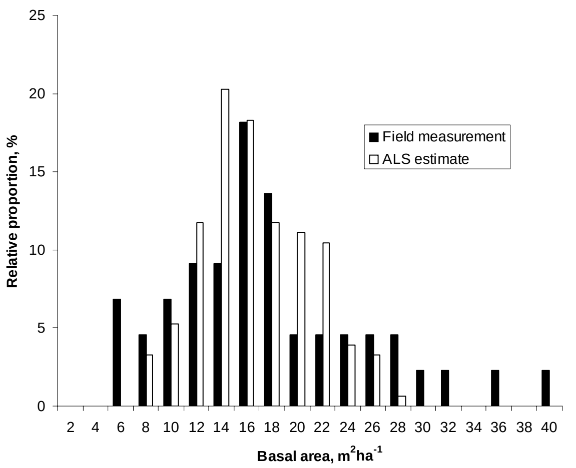

Fig. 4. Within stand distributions of field measured and ALS based basal area estimates. Field measurements: mean basal area 18 m^2ha^{-1} and number of field measured angle count plots 44. ALS: mean basal area 15.6 m^2ha^{-1} and number of grid cells 153. Area of the stand is 3.9 hectares.

As shown in the example figures (4 and 5) ALS data can reproduce realistic estimates of within stand variation of basal area. The averaging effect of models can be seen on both ends of the distribution since extreme values are not predicted. Compared to current field estimate of compartment inventory which is only average value of basal area in the stand this kind spatial information is of primary interest. As within stand variation can be described, the need for silvicultural operations such as thinnings can be more accurately timed and spatial pattern at stand level can also be defined. Of course, information presented in Figures 4 and 5 can also be produced by using single tree detection if as a result of it high proportion of trees are detected and accurate calibrated tree diameter model is used.

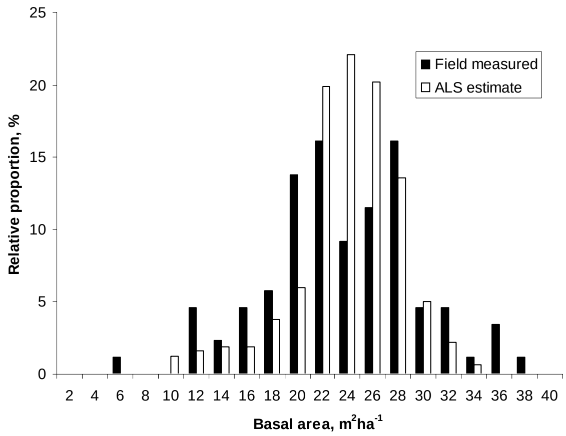

Fig. 5. Within stand distributions of field measured and ALS based basal area estimates. Field measurements: mean 24 m^2ha^{-1} and number of field measured angle count plots 87. ALS: mean basal area 22.9 m^2ha^{-1} and number of grid cells 327. Area of the stand is 8.4 hectares.

5. CONCLUSIONS

In Finland there are numerous research activities going on concerning the utilisation of ALS data in forest applications. First commercial ALS applications for forest inventory purposes were also introduced in Finland year 2006. This paper reviewed and discussed most of research works concentrating especially on forest inventory purposes. Some further utilisation possibilities, such as spatiality and biodiversity aspects in terms of CWD and large aspens, were also considered and proposed. There are also numerous other research topics, such as canopy cover, tree quality, forest condition, stand delineation, forest planning, site classification and forest structure which are currently examined in Finland by using ALS data. From the point of forest research both area based and single tree approaches have a very high potential to be further developed and used in novel applications. One possible application would also be a combination of area based and single tree detection methods. Also the rapid technological development of laser technology gives new possibilities all the time.

A lot of interest is currently being shown especially in remote sensing-based forest inventories in Finland, the driving force being the possibility for reducing costs, although the potential for improved accuracy is also important. Species-specific stand characteristics are essential in Finland, because they are used as an input to forest management planning. The accuracies achieved in the study by Packalén and Maltamo (2007) in the estimation of species-specific characteristics were at least as good as those achieved with the current inventory practise, but more testing must be carried out in different types of forests with varying species compositions, different geographical locations and different age distributions before it is fully justified to conclude that the combined use of ALS and aerial photographs prove superior to a conventional inventory by compartments (Packalén, 2006). The inclusion of young forests to inventory chain is also one research topic to be further examined.

ALS-based tree-level forest inventories may become a realistic alternative in the near future. Tree-level inventories require denser ALS data but technological development will mean that costs will decrease rapidly. An approach in which aerial photographs are not needed for species recognition would also be interesting at the individual tree level, but more development work must still be done in the fields of individual tree recognition, tree species classification, modelling tree variables, especially tree diameter and the inventory chain as a whole before tree-level inventories can be valid operationally.

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