MEASURING THE GROWTH OF INDIVIDUAL TREES USING MULTI-TEMPORAL AIRBORNE LASER SCANNING POINT CLOUDS

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ABSTRACT:

It is well known that characteristics of individual trees, such as tree height, biomass and crown area, can be derived from airborne laser scanning (ALS) and that heights for individual trees can be obtained with an accuracy of 0.5 to 1.5 m. However, the ability to measure the growth of individual trees using ALS has not been documented. This paper reports multi-temporal laser surveys conducted in a boreal forest zone suggesting that the height growth for individual trees can be measured with an accuracy better than 0.5 m. Methods to automatically extract height growth of tree crowns are presented. It is expected that similar methods are feasible for reference measurements in studies analyzing global forest changes and the carbon sink, in national forest inventories, and in describing the effects of global warming on forest growth.

1. INTRODUCTION

Forests are living ecosystems, influenced by continuous natural and anthropogenic processes. Natural forest processes include annual growth, mortality and natural disasters, whereas cutting and cultivation present typical anthropogenic actions.

Remote sensing techniques, especially optical and microwave satellite imaging, have been widely studied during the last decades with a view to supporting or replacing conventional forest inventories (e.g. Tomppo, 1997). Due to the high accuracy required in practical stand wise forest inventories, the success in using satellite data has been low. The development of computer technology and ALS has made it possible, since 1999 (Hyyppä and Inkinen, 1999; Brandtberg, 1999), to measure individual tree crown (ITC) properties using segmentation of 3D canopy height models and point clouds. Numerous studies have indicated that, for example, mean height, basal-area and stand volume can be accurately predicted using laser scanning (Næsset, 1997a,b; Magnussen and Boudewun, 1998; Lefsky et al., 1999; Means et al., 2000; Næsset, 2002). Individual trees have been reported to be detected with up to 70% correctness (Persson et al., 2002) and tree height with a standard error ranging from 0.5 to 1.5 m (Hyyppä and Inkinen, 1999; Persson et al., 2002; Gaveau and Hill, 2003).

The detection of changes in forested areas using remotely sensed imagery has so far not been accurate enough to meet the assessment requirements, especially regarding slight or moderate changes such as thinning or forest damage (Häme, 1991; Olsson, 1994; Varjo, 1996). Laser scanning has been recently used for change detection and shown a great potential for forest growth estimation (Yu et al., 2003; Hyyppä et al., 2003; Yu et al., 2004; St-Onge and Vepakomma, 2004; Gobakken and Næsset, 2004). Yu et al. (2003, 2004) demonstrated the applicability of small footprint, high sampling density airborne laser scanners for boreal forest change detection, i.e. the estimation of forest growth and monitoring of harvested trees. Two laser acquisitions were carried out on a test site using a Toposys-1 laser scanner. Algorithms were developed for detecting harvested and fallen trees, and for measuring forest growth at plot and stand levels. Out of 83 field-checked harvested trees, 61 could be automatically and correctly detected. All mature harvested trees were detected; it was mainly the smaller trees that were not. Forest growth was demonstrated at plot and stand levels.

Due to the errors in tree height estimation, the slow growth rate of trees and difficulties in accessing high-density laser data enabling individual tree estimation, quality of individual tree growth has not been reported earlier. We propose that laser scanning can also be applied in detecting the growth of individual trees in a high accuracy.

2. STUDY AREA AND DATA SETS

2.1 Test Site

The test site was placed in a boreal forest zone in Kalkkinen, 130 north of Helsinki, in Finland. The 2 km x 0.5 km area is situated about 110 m above sea level and dominated by small hills. The main tree species are *Picea abies* (Norway spruce) (49%), *Pinus sylvestris L.* (Scots pine) (35%), *Betula verrucosa* and *Betula pubescens* (silver and downy birches) (11%).

2.2 Laser Acquisitions

In order to demonstrate the possibility of measuring tree growth, multitemporal airborne laser scanning surveys were conducted. Using a Toposys-1 laser scanner, georeferenced point cloud data was collected from Kalkkinen on 2-3 September 1998 and 15 June 2000, and the same was done on 14 May 2003 using a Toposys Falcon scanner. The major difference between the Toposys-1 and Falcon was the possibility to record first and last pulse simultaneously with version Falcon. The technical specification of the system was given in Table 1. The test site was measured in each case from an altitude of 400 m (above ground level, a.g.l.) resulting in a nominal sampling density of about 10 measurements per m^2. This altitude was selected in order to provide the number of pulses needed to resolve individual trees. Both first and last returns were recorded. Only first returns were used in the analyses.

Parameter	**Performance(s)**
Sensor	pulse-modulated see www.toposys.com
Laser pulse frequency	83 000 Hz
Scan frequency	653 Hz
Field of view	± 7.1 degrees
Measurement density	Ca. 5 pulses per m^2 at 800 m Ca. 10 pulses per m2 at 400m
Beam divergence	1 mrad
Number of shots per scan	128 parallel shots (one of which is the reference)
Laser classification	class 1 by EN 60825 (eye-safe)

Table 1. TopoSys-1/Falcon performance parameters.

2.3 Reference Data

153 pines were selected and height, location and shoot elongation of these trees were measured in August 2002 and November 2004 using a tacheometer. In addition to measuring the height of the trees, three to six consecutive shoots below the top of the tree were also measured. This gave the height of the tree after each annual growth period between 1998-2004. The accuracy of the reference measurements was about 10-15 cm. The descriptive statistics of the reference measurements are shown in Table 2. In boreal conditions the annual growth period of pines lasts approximately from the beginning of May to mid-June (Kanninen et al. 1982). Due to the long winter in 2003, the growth of trees had not been initiated before the laser campaign on 14 May. Thus the difference between the September 1998 and May 2003 ALS surveys corresponded to four years of height growth of the trees. Terrestrial panoramic images were taken simultaneously with the ALS surveys to demonstrate the pulses hitting the tree tips, Figure 1.

	Height (m) in 2004	Growth between year (m)		
		1998 – 2000	2000 – 2003	1998 – 2003
Min	4.14	0.10	0.19	0.32
Max	32.33	1.44	1.91	3.07
Mean	20.84	0.43	0.66	1.07
S.D.	7.19	0.25	0.41	0.62

Table 2. Descriptive statistics for trees measured in the field.

3. METHODS

3.1 Classification of Laser Point Clouds

Laser data was first classified as ground and non-ground points using TerraScan software (see www.terrasolid.fi) based on a TIN densification method developed by Axelsson (2000).

3.2 Co-registration of Data Sets

For comparisons of the height of forest canopy at different dates laser data acquired at different surveys must be registered in order to eliminate the systematic errors between laser acquisitions. In this study, three laser datasets from year 1998, 2000 and 2003 were registered with ground truth which are the tachometric measurements of ground elevation in eight test plots of the test area (total 2200 points), depicted in detail in Hyyppä et al. (2005). Classified ground points were used for registration between the laser data and ground truth because the terrain is stable in the area. The iterative closest point algorithm (ICP) was used for registering two 3D point sets (Nikolaidis and Pitas, 2001). ICP algorithm was simplified to consider only shifts in X, Y and Z direction between two datasets. Registration was done separately for plots and mean value of these plots were applied for transforming the laser data. For 2000 and 2003 data the shifts in X and Y were small (<5 cm). The X and Y shifts were 13.9 and 31.5 m for 1998 data because of the systematic error in coordinate transformation of the data provider. In Z direction, the shifts were 2.54, 0.19 and 0.05 m for 1998, 2000 and 2003 data respectively. In general, the elevation of the point clouds can be calibrated using surfaces, such as roads and lower branches, on various parts of the digital surface model. The shifts between the digital surface models could be calibrated using breaklines, such as ridges of house roofs, if they are available in the images.

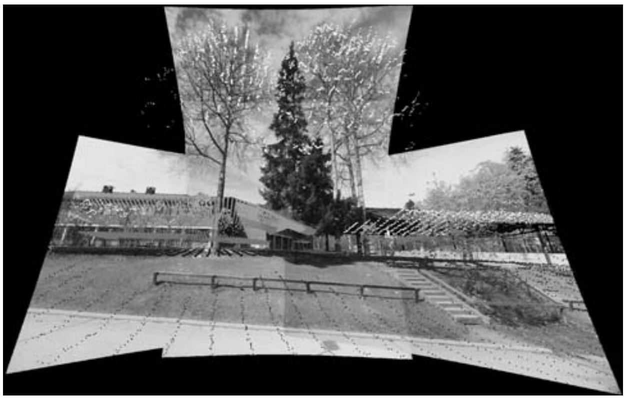

Figure 1. Toposys laser data from the year 2003 is superimposed on the geometrically corrected terrestrial panoramic image.

3.3 Identification of Trees And Extraction of Variables

For each tree measured in the field, the laser points falling into a cylinder around the location of the selected tree were used for extract variables used for growth estimation. The radius of the cylinder is determined by tree height since the tree height is correlated with crown diameters. In this study, the extracted variable is maximum z value (MaxZ) of the raw point clouds besides the maximum canopy height among the points inside the cylinder. The use of raw laser measurements for growth calculations can avoid the errors caused by DTM and other intermediate procedures when canopy height was calculated.

3.4 Growth Calculations

Tree height growth was calculated as the differences of the extracted values (MaxZ, canopy height) from two datasets and compared them with the corresponding field-measured values. The regression analyses were performed. Systematic error was calculated as mean differences between laser-derived growth and field-measured one, whereas the random error was obtained from standard deviation of the difference.

4. RESULTS

Figure 2 shows point clouds of an example tree corresponding to airborne laser scanning surveys in 1998 (blue), 2000 (pink) and 2003 (yellow). Obviously, the point clouds represent the tree growth, both in height and in diameter.

Figure 3 shows the scattergraph and regression line between the laser-derived growth and field-measured growth. The coefficient of determination (0.66) between acquisitions in 2003 and 1998 indicates that it is possible to measure the growth of an individual tree. RMSE of individual growth was approximately 45 cm and the bias was 10 cm, indicating an overestimation of the growth by the laser. The bias of the growth between acquisitions in 2000 and 1998 was 0 cm and between acquisitions in 2003 and 2000 was 11 cm. The reason for the biases is most likely to be changes in the sensitivity of the instruments. It seems that the Toposys Falcon is more sensitive than its predecessor Toposys-1. The measurement in early season did not affect on pine trees selected for the study.

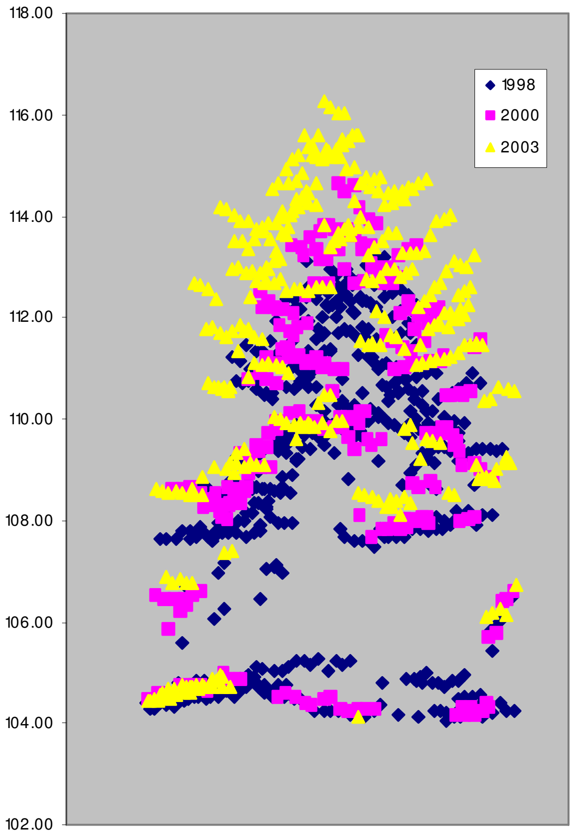

Figure 2. Tree growth is visible when multitemporal ALS data are examined together from a side perspective: blue, pink and yellow correspond to acquisitions in 1998, 2000 and 2003, respectively. The data sets have been co-registered.

The standard deviation of the growth between acquisitions in 2000 and 1998 was 46 cm and between acquisitions in 2003 and 2000 was 38 cm. Most probably the errors related to airborne laser scanning are decreasing as the ALS technology is improving. It is expected that improvements in GPS and IMU technology have reduced the planimetric errors troubling the tree-to-tree matching between data sets.

Figure 4 shows empirically that the taller trees growth more slowly than the young ones and less variation were observed for taller trees than for young ones.

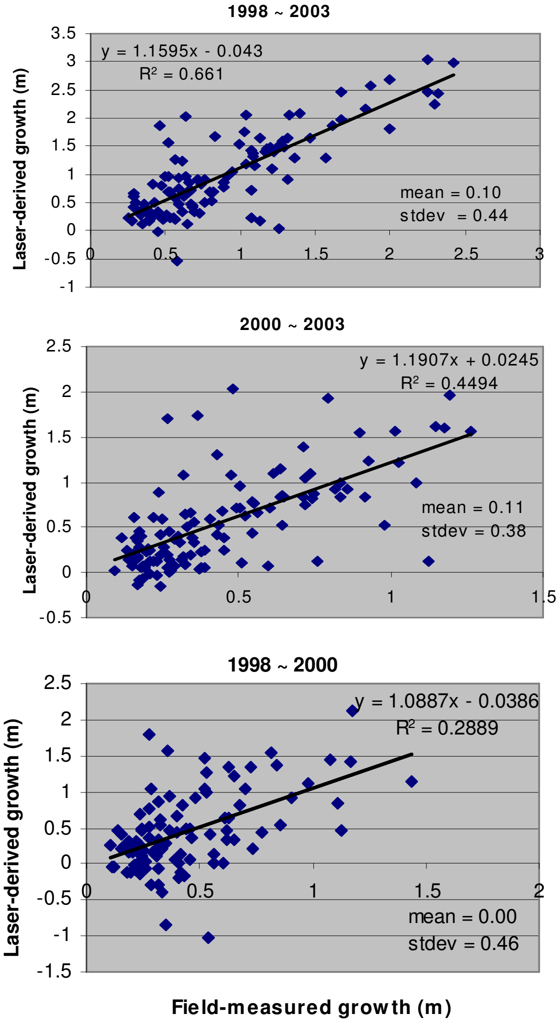

Figure 3. The scattergram and regression line between the field-measured growth and laser-derived growth. As can be seen, the variation of laser-derived growth is higher than field-measured growth due to the inaccuracy of the ALS system in measuring tree tops.

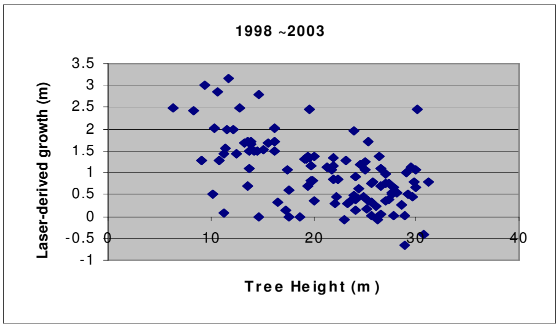

Figure 4. Laser-derived growth as a function of tree height.

5. DISCUSSION

Both RMSE and bias are lower than those reported in an earlier study concerning field measurements of height growth (Päivinen et al. 1992). In general, height increment of older trees is very difficult to assess in the field and only seldom it is measured from sample trees.

The major reasons for largest errors in the analysis include the boundary effect, i.e. the location of the tree in one of the datasets is near the boundary of the data area and that wrong tree was identified in one of the datasets. This was happened when there was a taller tree nearby and some branches overlap with the object tree.

Co-registration of multi-temporal datasets is important for tree growth analyses as in any kind of change detections. In this study, remaining distortions after the co-registration are very small. Their impact on the growth can be ignored.

With respect to earlier studies, improvements in growth analysis (Yu et al., 2003; Yu et al., 2004) include the ability to estimate individual tree growth using point clouds and eliminating the error source, i.e. from using the digital elevation model. Automatic individual tree growth analysis requires proper isolation of individual tree crowns and tree-to-tree matching (i.e. locating the trees and solving the location ambiguity at the time of acquisition) between various acquisitions. In addition to these errors, there are other factors that may cause changes to the forest growth estimates. Weather conditions, such as strong winds, cause displacements of tree crowns. The applied georeferencing technology, i.e. the use of inertia measurement unit (IMU), may cause planimetric errors of several decimetres. The use of higher flight altitudes (a.g.l.) increases the IMU related errors. The same target can also be measured with two different geometries (e.g. from opposite directions), resulting in significant differences in point clouds. It is recommended that the technique called repeat pass airborne laser scanning be used

There are several ways to reduce the errors in growth estimation.

- The use of a system with same or similar characteristics for the measurement campaigns could reduce the errors in growth analysis.
- If surveys were conducted with the same flight planning information, individual trees would be viewed from the same direction and this would further reduce the errors in growth analysis.
- Growth values less than zero should not be accepted.
- Growth values exceeding knowledge-based upper and lower-bounds could be estimated from the height of the trees. In Figure 4, it was shown that height and growth correlated.
- When growth at individual tree level is not required, then growth values outside upper and lower bounds can be rejected. Additionally, the large deviations (behave such as outliers) can be eliminated by having higher weight of those growth values within 25% and 75% percentiles.

Presently, the availability of laser data is improving significantly each year and the costs are steadily decreasing due to the new system enabling higher sampling densities and higher flight altitudes. Most of the presently available laser systems can detect individual trees. Present costs for laser surveys are highly dependent on the size and shape of the test site and wanted pulse density, the costs ranging being 0.5-4€/ha. In traditional forest inventories, the costs for permanent sample plots (e.g. 20 m by 20 m) are normally 100-200€ per plot. The most economic use of the presented method is to apply it to the strip-based sampling, since long strips are economic to fly. Thus, large-area forest inventories using permanent or non-permanent sample plots are perhaps the most feasible operative applications for the presented method. The technique presented is also economically feasible for monitoring trees in city parks and monitoring of tree height growth near runaways for flight obstacle mapping. In both of them, high density laser data is already applied.

6. CONCLUSIONS

This paper reports multi-temporal laser surveys conducted in a boreal forest zone suggesting that the height growth for individual trees can be measured with an accuracy better than 0.5 m.

When integrated with individual tree based inventories the proposed technique is likely to be highly suitable for the development of new generation forest growth models. When tree locations, their attributes, their growth, and how they cast shadows on each other are known, improvements in forest growth modelling can be expected. Additionally, individual tree based inventories and repeated airborne laser scanning should prove to be effective data collecting techniques, e.g. as strip-based sampling, in future national forest and carbon sink inventories, where permanent sample plots are placed across a country.

Our planet is facing severe global changes, such as climate change (and its effects on forest growth), vegetation redistributions and anthropogenic changes, especially in tropical forests; using multi-temporal airborne laser scanning surveys at fixed locations across selected areas could be one way of collecting objective reference data of these changes in order to support the global decision making process.

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