FOREST DATA CAPTURE USING OPTICAL 3D DIGITAL SURFACE MODELS FROM THE C3 TECHNOLOGIES SYSTEM

Jörgen Wallerman, PhD
Jonas Bohlin, MSc
Johan E. S. Fransson, Associate Professor
Remote Sensing Laboratory
Swedish University of Agricultural Sciences
SE 901 83, Umeå
Sweden
jorgen.wallerman@srh.slu.se
jonas.bohlin@srh.slu.se
johan.fransson@srh.slu.se

Kristian Lundberg, Adviser, Concept Development
Saab Bofors Dynamics AB,
SE 581 88 Linköping
Sweden
kristian.lundberg@saabgroup.com

ABSTRACT

Recent development of airborne optical systems acquiring multiple-view image data and fast photogrammetric processing algorithms have provided the Swedish market with new sources of 3D Digital Surface Models (DSMs) of the landscape. In particular, a very promising system has been developed by Saab Bofors Dynamics and operated by C3 Technologies. It has been applied successfully to map the major cities of Sweden and Norway in order to rapidly provide highly detailed 3D models of city buildings and infrastructure. The system has an inherent capacity to quickly map and process data from very large areas, which in combination with accurate DSM generation could provide a new and valuable source of data for forest management planning. This is especially true in Sweden today, since the Swedish National Land Survey has decided to produce a new, highly accurate Digital Elevation Model (DEM) of the country using Airborne Laser Scanning (ALS). Using the new DEM and the DSM created by C3 Technologies may provide useful information about the forest, such as tree height, stem diameter and stem volume.
This paper presents the first evaluation of the forest information content using a DSM from C3 Technologies and an accurate DTM derived from ALS data. The study was carried out in a mixed coniferous forest area in Southern Sweden (Lat. 58°38'28", Long 15°19'34"), where field data with accurate measurements of position, height and stem diameter of all trees were available. Using the difference of the DSM and the DEM, the vegetation canopy height was assessed. Automatic single tree detection was then performed, followed by estimation of height, stem diameter and stem volume of each detected tree.

Key words: Forest, optical, surface models, 3D.

INTRODUCTION

The recent rapid development of airborne high-resolution optical systems has provided new possibilities to efficiently map the forest in Sweden. Several operational Swedish sensor systems acquire multi-view optical image data, which can be used in photogrammetric processing (e.g. Baltsavias et al., 2008; Hirschmugl, 2008) to provide 3D data of forest, i.e. a complete area-coverage with raster measurements of tree height, for large areas at a low cost. A promising system is Rapid Mapping, a photogrammetric system and photogrammetric processing software developed by Saab Bofors Dynamics and operated by C3 Technologies, which have recently been extensively applied to cost-efficiently map the major cities in Sweden and Norway in 3D. The system simultaneously produces accurate 3D models, i.e. Digital Surface Models (DSMs) of the photographed area, and spectral RGB image data for a large number of view angles. These city mapping missions have provided data for interactive, detailed 3D presentations of the cities on the Internet (e.g. www.hitta.se). Also, in operational use is the Z/I DMC photogrammetric camera, the new standard camera for the nation-wide aerial photography program executed by the Swedish National Land Survey (NLS). Currently, SNLS plans to map approximately one-third of Sweden's land area each year using the Z/I DMC. Hence, reasonably new Z/I DMC data from the standard survey design will be available nation-wide at a low cost, providing spectral and also DSM data of the vegetation canopy height.

Capture of tree height data using DSMs generated from optical data only is not expected to be successful, since ground level is not easily assessed using optical image data alone. This problem will be solved by another recent and major effort by SNLS, which is the new nation-wide Airborne Laser Scanning (ALS) program, being carried out between 2009 and 2013 in order to acquire a new accurate Digital Elevation Model (DEM) of Sweden. The DEM production and the new accurate DSM generation may very well constitute highly cost-efficient data sources to support forest management planning. This support would be efficient for private forest owners tending small areas as well as for forest companies managing very large areas. Furthermore, there is also potential for environmental mapping, such as data capture for modeling endangered species habitat, carbon sequestration management planning, and many more applications requiring accurate data over large areas at a reasonable cost.

The predictive capacity of accurate tree canopy height data is well known from past research of ALS applications for forest data capture (e.g. Næsset et al., 2004). In short, ALS emits 50 000 – 300 000 pulses/s in a regular pattern beneath the air vessel and records the distance to whatever object on the ground each pulse hits. Processing of the data provide point clouds, with horizontal and vertical coordinates (accuracy in the order of 0.1 m) for each hit, classified as probable hits of the ground or the vegetation. This is then easily converted to measurements of the vegetation canopy height over ground, vertical density distribution, and several other measures. Research on ALS for forest mapping has been made since the early 1990s (Næsset et al., 2004) and in boreal forest environments yields prediction accuracies of 2.5–13.6%, 5.9-15.8% , and 8.4-16.6% RMSE for mean tree height, mean stem diameter, and mean stem volume, respectively (Næsset et al., 2004). Utilizing optical DSM data from the UltracamD system, in combination with accurate DEM data, Hirschmugel (2008) obtained RMSEs of 4.7 and 2.5 m for tree height estimations.

Assessment of tree species information is clearly of fundamental importance for most forestry and environmental management applications. Promising results have been obtained using Z/I DMC NIR spectral data (Holmgren and Persson, 2004; Olofsson et al., 2006). In these studies, color data of only the sun-lit part of each tree were utilized in discriminant analysis, and Holmgren and Persson (2004) report 85% classification accuracy (pine, spruce or broad-leaf) of the visible trees. Furthermore, new methods to address the calibration problem of view-angle dependent varying spectral reflectance have been developed, using a satellite image as common reference (Holopainen and Wang, 1998 Tuominen and Pekkarinen, 2004). Utilizing high resolution (< 0.1 m pixel size) aerial imagery has also revealed potential for tree species discrimination through the use of advanced pattern-recognition algorithms applied to detect the species-dependent branch structures (Brandtberg, 1999), rather than relying on species-dependent spectral variation only.

The Rapid Mapping system makes available a combination of high resolution (0.1 m pixel size) DSM and spectral data, which can possibly provide data for accurate estimation of forest size parameters as well as assessment of tree species information. Furthermore, the high resolution data also provide the possibility to automatically detect single trees in the forest, since the scale of trees is much larger than the spatial resolution of the data.

This paper presents the first pilot study assessing forest information content of the data provided by the Rapid Mapping system. The aim is to evaluate a single-tree detection approach applied on DSM data only, and assess the accuracy of single-tree estimated tree height, stem diameter and stem volume. The study is carried out using data from a test site, Kvarn, in Southern Sweden, where a field dataset of accurately measured and positioned trees has been collected, as well as densely scanned ALS data providing an accurate DEM. At the Kvarn test site, DSM data are available from the first operational Rapid Mapping system. Unfortunately, data acquired by the significantly upgraded system, which is used operationally today, are not available at the time of this analysis.

TEST SITE AND IMAGE DATA

The test site is situated in Southern Sweden, close to Kvarn (Lat. 58°38'28", Long 15°19'34") in the county of Östergötland. It is part of a military exercise area and managed by the Land Warfare Centre of the Swedish Armed Forces. In the area, five field plots (50 by 50 m and 30 by 80 m) were surveyed in December 2006 to provide accurate single-tree ground truth data (Table 1). The plots were allocated in forests of different tree species composition and ages. All trees on the plots were measured manually (stem diameter 1.3 m above ground, tree height, and stem inclination), and position of each tree was accurately measured using a total station and RTK GPS.

Table 1. Forest characteristics of the field plots

Plot	Size [m]	Tree diameter (min / mean / max) [cm]	Tree height (min / mean / max) [m]	Mean stem volume [m^3/ha]	Mean stem density [stems] / [stems/ha]	Species composition (pine/spruce/deciduous) [% of stem volume]
1	50 × 50	5.2 / 26.4 / 54.0	2.3 / 21.9 / 31.0	396	127 / 508	10 / 87 / 3
2	50 × 50	5.2 / 18.2 / 28.9	3.4 / 15.0 / 19.1	184	220 / 880	3 / 95 / 2
3	50 × 50	5.5 / 17.8 / 37.2	2.0 / 15.0 / 24.3	116	136 / 544	11 / 2 / 87
4	50 × 50	5.0 / 20.0 / 33.4	2.0 / 13.5 / 18.8	138	160 / 640	71 / 28 / 1
5	30 × 80	5.8 / 22.7 / 40.2	3.0 / 19.3 / 24.8	513	304 / 1267	61 / 39 / 0
All		5.0 / 21.0 / 54.0	2.0 / 17.0 / 31.0	269	947 / 763	34 / 57 / 9

The laser scanning was made in 2006 using the TopEye ALS system mounted on a helicopter, with a nominal density of 50 emitted pulses / m^2. Following a standard vegetation/ground classification of the laser hits, the ground measurements was used to calculate a DEM with 0.25 m cell size. Optical image data were acquired in July 2007 using the Rapid Mapping system, which consists of 5 standard cameras and an integrated navigation system for accurate positioning and attitude determination of the camera cluster. Georeferenced images with a pixel size of 0.10 m were produced at an operational speed of 90 m/s and an altitude of 600 m.

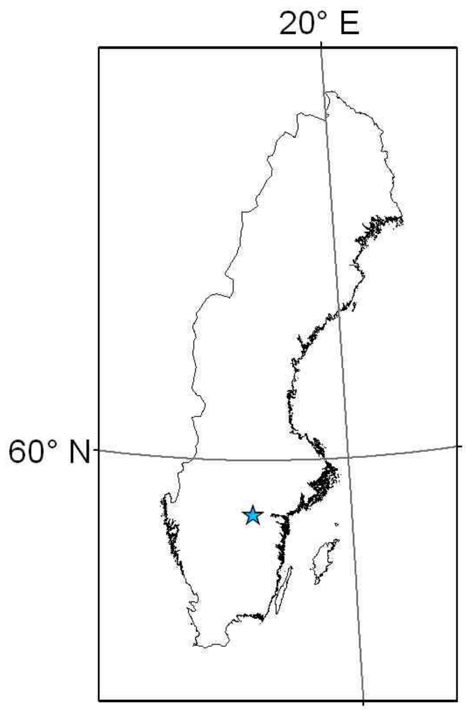

Figure 1. The location of the Kvarn test site.

ANALYSIS

The single-tree detection approach is based on the assumption that each local maxima in the DSM corresponds to one tree on the ground, and uses local DSM statistics to predict the characteristics of each tree. In order to model the relation between tree characteristics and DSM data, a field sample of accurately positioned and measured trees is also needed. The analysis was made in four steps:

1) Segmentation of the DSM,
2) Relating each field measured tree to a corresponding segment,
3) Modeling tree height, stem diameter, and stem volume from field measurements and DSM data,
4) Evaluation of tree parameter estimation accuracy.

Spatial positions and crown extents of visible trees were estimated using a segmentation algorithm developed for single-tree detection in ALS data (Holmgren and Wallerman, 2006). This process aims to identify every local maxima in the ground-level corrected DSM, and extract DSM amplitude and spatial position of each maxima. Furthermore, segmentation also delineates the area surrounding each maxima and enclosed by DSM inflexion raster cells, to provide information about tree crown extent. The utilized segmentation algorithm consists of a first step of matching a large number of geometric templates (generalized ellipsoids of revolution (Pollock, 1996)) to every cell center in the DSM, evaluating the fit to the DSM using cross-correlation. The result is stored as a new raster where each cell contain the cross-correlation of the best template fit in each cell position. In the second step local maxima and segment boundaries are assessed using an iterative search in the raster with correlation values (Holmgren and Wallerman, 2006). Finally, at each assessed local maxima, the DSM value (*H*) and segment area were stored to be used as independent data for statistical modeling of tree parameters. Segment area was transformed to diameter length (*W*) of a circle with area of corresponding size.

An attempt to relate each field measured tree to the most likely segment using the automatic matching algorithm developed by Olofsson et al. (2008). This method aims to fit a model of the spatial pattern of field measured trees to a similar model of the segmentation results, in order to correct positional inaccuracies and to link each field measured tree to the corresponding DSM local maxima. Modeling is made using spatial Gaussian kernels, centered at each measured tree position and DSM maxima, and scaled by the measured tree diameter and DSM height value, respectively.

Furthermore, regression models were fitted to model tree height, stem diameter, and stem volume, using *H* and *W* as independent variables.

Finally, prediction accuracies of the forest parameters were assessed at tree level using leave-one-out cross validation, and at plot level without cross validation, to calculate Root Mean Square Error (RMSE).

RESULTS

The results of the single tree detection (Figure 2) and automatic matching of field measured trees to segments could be improved. In the matching procedure, several segments were not linked to a field measured tree, and several field measured trees were not assigned a segment. As seen in Figure 2, the detection of trees did not fully correspond to the field dataset, showing large variation depending on forest structure, i.e. the green and red symbols do not fully coincide. Using data from the linked trees and the corresponding DSM measures *H* and *W*, DSM height (*H*) showed strong and linear dependence on field measured tree height (Figure 3). In Figure 3, DSM height is also plotted against field measured stem diameter revealing a weak and non-linear relationship. These data were used to fit linear models of tree height, and log-linear models of stem diameter and stem volume (Table 2). Correction factors, *l*, for logarithmic bias were calculated according to Holm (1977). The adjusted coefficient of determination was found to be in the range of 0.65-0.95, 0.49-0.74, and 0.56-0.84 for tree height, stem diameter and stem volume respectively.

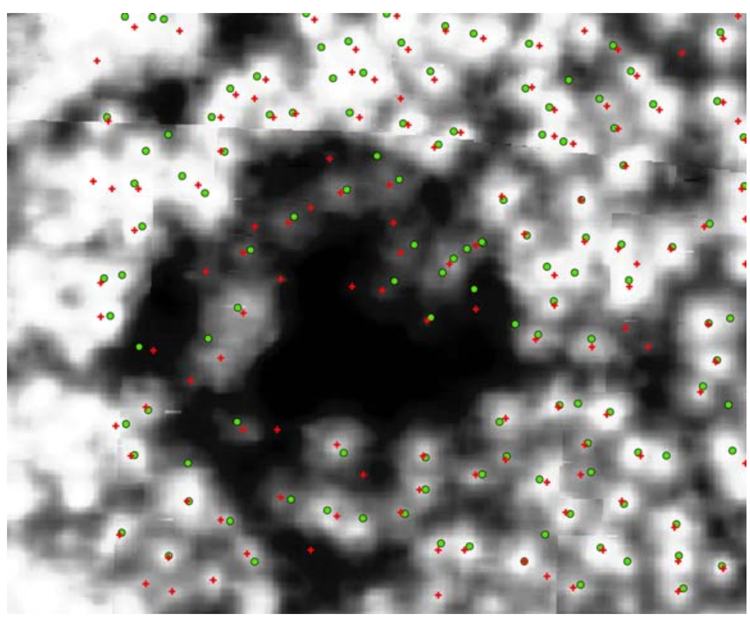

Figure 2. DSM map and tree detection results of field plot 2 (green dots are positions of field measured trees, red crosses are detected trees).

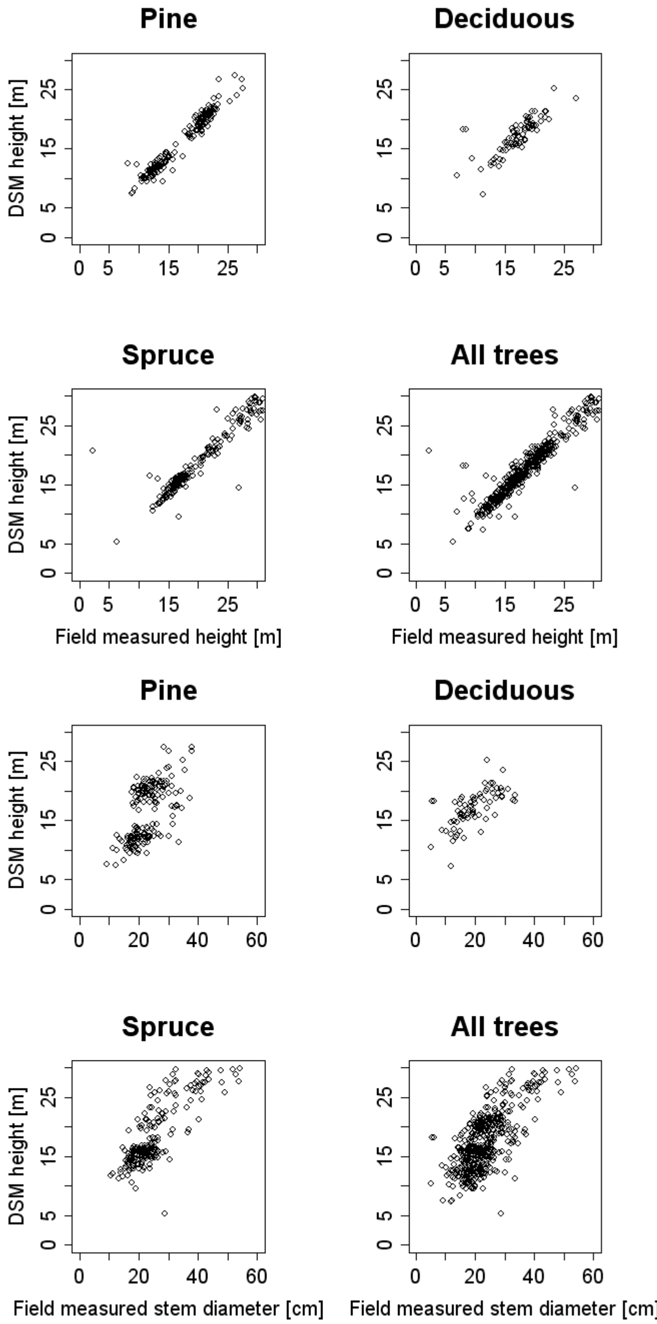

Figure 3. Scatterplots of sample tree measurements and DSM height (*H*).

Table 2. Regression model parameters (Tree height in [m], stem diameter in [cm], and stem volume in [dm^3])

†) Parameter not significant ($p > 0.05$).

Model		Intercept	*H*	*W*	Adj. R^2	*l*
Tree height	Pine	1.96	0.943		0.95	
Tree height	Spruce	2.02	0.956		0.87	
Tree height	Deciduous	2.00†	0.775	0.390	0.64	
Tree height	All	1.72	0.956		0.87	
ln(Stem diameter)	Pine	4.71	0.0290	0.0570	0.49	1.01
ln(Stem diameter)	Spruce	4.53	0.0352	0.0707	0.74	1.01
ln(Stem diameter)	Deciduous	3.98	0.0443	0.101	0.55	1.02
ln(Stem diameter)	All	4.54	0.0350	0.0631	0.54	1.02
ln(Stem volume)	Pine	3.55	0.108	0.103	0.72	1.04
ln(Stem volume)	Spruce	3.38	0.115	0.118	0.84	1.04
ln(Stem volume)	Deciduous	2.11	0.128	0.201	0.56	1.06
ln(Stem volume)	All	3.28	0.118	0.104	0.67	1.08

In Table 3, the accuracy assessment in terms of RMSE at tree level is presented. The results show lowest RMSE for tree height, and higher for stem diameter and stem volume. All models were found to be unbiased except for the stem volume of deciduous trees, showing a bias of 6.3%. Furthermore, there is variation among the tree species for each of the forest parameter (Table 3). At plot level, the RMSEs for basal area weighted mean tree height, basal area weighted mean stem diameter, stem density, and mean stem volume, were 2.4 m (corresponding to 12% of the true basal area weighted mean tree height), 3.7 cm (13%), 257 stems/ha (20%), and 57 m^3/ha (11%) (Table 4).

Table 3. Cross-validation accuracy of single tree models (predicted – true value) in percent of true mean

Model	Tree height (RMSE / bias) [%]	Stem diameter (RMSE / bias) [%]	Stem volume (RMSE / bias) [%]
Pine	6.0 / 0.0	17 / 0.0	35 / 0.0
Spruce	10 / 0.0	17 / 0.0	40 / 0.1
Deciduous	13 / 0.0	23 / 0.1	50 / 6.3
All	9.5 / 0.0	19 / 0.0	43 / 0.0

Table 4. Prediction errors of plot mean values

Plot	Basal area weighted mean tree height [m]	Basal area weighted mean stem diameter [cm]	Stem density [stems/ha]	Mean stem volume/ha [m^3/ha]
1	-2.1	-6.4	168	55
2	-0.90	-1.6	236	33
3	-0.31	-2.2	272	98
4	-0.61	-3.6	404	41
5	-0.03	-2.4	95	29
RMSE	2.4	3.7	257	57

DISCUSSION

In this paper, the forest information content derived from the airborne optical Rapid Mapping system and TopEye ALS system was investigated and evaluated using a single-tree detection approach. Based on a DSM generated from the optical system, a DEM produced from the ALS and an extensive field dataset collected over a mixed coniferous test site located in Southern Sweden, the accuracy of estimated tree height, stem diameter and stem volume at tree and plot level were assessed.

The results at tree level show that the Root Mean Square Errors (RMSEs) for tree height, stem diameter, and stem volume were 9.5%, 19% and 43%, respectively. The corresponding figures at plot level were found to be 12%, 13% and 11%. Thus, the tree height prediction yielded similar results at the tree as well as at the plot level. For stem diameter and stem volume, however, the results at the plot level are superior. At tree level, Hirschmugel (2008) reported RMSEs of 4.7 and 2.5 m for tree height estimations, to be compared to 1.6 m (9.5%) obtained in the present study. Furthermore, the plot level results obtained in the present study are also in good agreement with previously presented studies using ALS data, e.g. Næsset et al., (2004). In Næsset et al. (2004), the prediction accuracies of 2.5–13.6%, 5.9-15.8%, and 8.4-16.6% RMSE for mean tree height, mean stem diameter, and mean stem volume, respectively, are reported for forest stands with a stem volume in the range of 153-287 m^3/ha. The results of this study are also in agreement, or slightly better, than the results using subjective field surveys methods presented in Ståhl (1992), where stem volume was estimated with a standard error of 13.5%. It is likely that the range of the investigated stem volume can explain the differences in stem volume accuracy between Ståhl (1992) and the present study, i.e., stem volume range of 70-350 m^3/ha in comparison to 115-515 m^3/ha (Table 1). The tree height accuracy expressed in RMSE was on average 8.4% in comparison to about 9% in Ståhl (1992).

From Figure 3. it is obvious that the obtained tree height information using the proposed method is accurate, when evaluated on the field trees connected with a segment (see scatterplot above). However, the segmentation and matching method did not perform well when applied on non-ALS data, and are an issue for further research.

The Rapid Mapping system shows clear potential for forest survey applications, since the reported accuracies well fulfill the common requirements for forest management planning purposes. Especially, the plot level results are comparable with those obtained using ALS data. Forest structure seem to affect the results, as well as tree species composition, which imply that species stratification should be included in further investigations. It should also be noted that the dataset from which the results were derived was limited, and that the used sensor system now is replaced by the new, upgraded Rapid Mapping system.

In summary, the results imply that the combination of DSM and DEM data derived from the Rapid Mapping and TopEye ALS systems have significant potential for operational use in forestry applications.

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