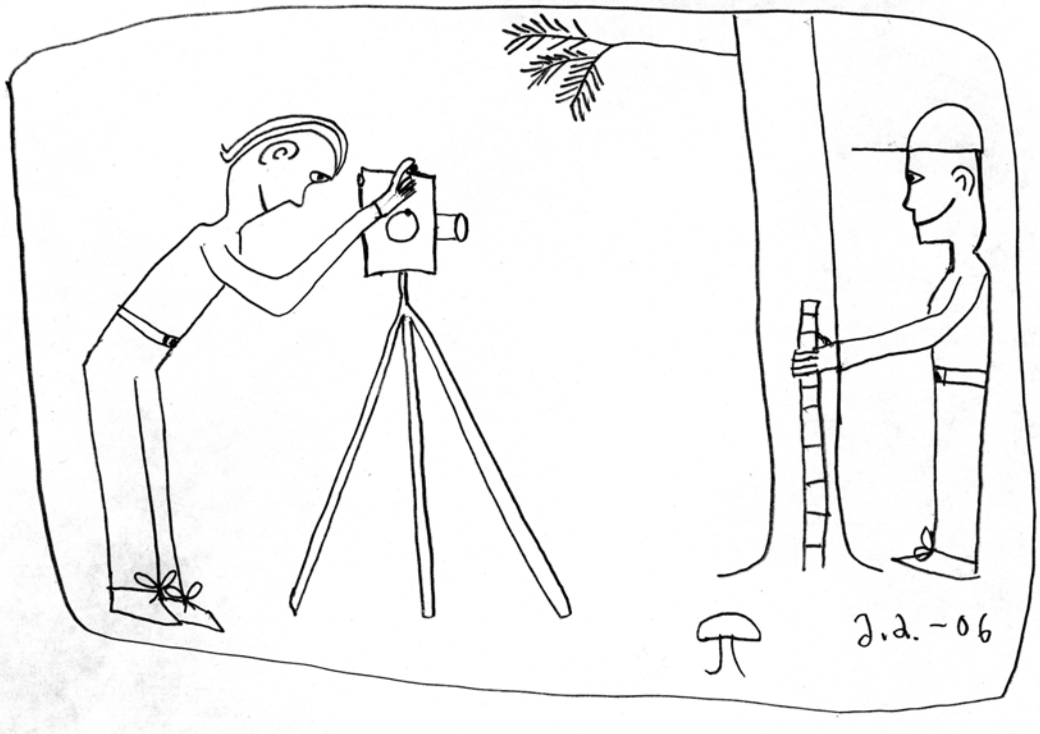
Working Papers of the Finnish Forest Research Institute 40

http://www.metla.fi/julkaisut/workingpapers/2006/mwp040.htm
ISBN-13: 978-951-40-2026-1 (PDF)
ISBN-10: 951-40-2026-X (PDF)
ISSN 1795-150X

Digital horizontal tree measurements for forest inventory

Jari Varjo, Helena Henttonen, Juha Lappi, Jukka Heikkonen and Jouni Juujärvi



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http://www.metla.fi/julkaisut/workingpapers/
ISSN 1795-150X

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http://www.metla.fi/

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Year	**Pages**	**ISBN**	**ISSN**
2006	23	ISBN-13: 978-951-40-2026-1 (PDF) ISBN-10: 951-40-2026-X (PDF)	1795-150X

Unit / Research programme / Projects

Vantaa Research Unit and Suonenjoki Research Unit/
Measurement of trees by applying digital images in forest inventory/40400

Accepted by

Heikki Smolander, Director of Suonenjoki Research Unit, 8.12.2006

Abstract

Scots pine tapering and stem volume estimation was tested by photographing single pine stems in normal Boreal forest conditions with a simple digital camera. In the volume estimation a new methodology was developed where a tapering model was used to supervise the image interpretation. The results were compared with traditional methods by felling and manually measuring the test trees on the ground. The developed method resulted in a -0.6mm - -2.8 mm bias and 7.0 mm - 9.4 mm RMSE in diameter estimates and 0.4 % bias and 7.3 % RMSE in volume estimates. The achieved accuracies of the diameter and volume measurements were at comparable levels with traditional volume estimates based on measurements of height and one or two diameters. This level of accuracy was considered satisfactory. However, the variation in the photographing conditions and the performance of the simple digital camera did not always produce the required image quality for further analysis.

Keywords

digital measurement, stem tapering, forest inventory

Available at

http://www.metla.fi/julkaisut/workingpapers/2006/mwp040.htm

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Preface

1. Introduction

A common measurement problem is how to obtain a high degree of accuracy with minimum bias at low cost. To avoid aggregation of errors when calculating results for large areas applications such as national forest inventories also aim for unbiased results. In forest measurement the stem volume is probably the most common independent variable. Generally it is estimated as a function of two or three dimensions of a tree. These dimensions are the diameters at different heights and the height of the stem. When the diameters of the stem are expressed as a continuous function, for example of the height, they constitute a tapering curve of a tree.

Tapering has been estimated from film camera photographs (v. Dehn et al. 1985); stem diameters have been measured from digital photographs (Clark et al. 1998) and a multi-sensor video system (Clark et al. 2000, Clark 2001) has been tested by measuring the diameters of the image and transforming them to physical units by trigonometry. However, these methods require a rather complex measurement installation i.e., detection of the present observation angles required in trigonometric equations. In addition, in order to be taken into practical use it would be an advantage if the whole measurement procedure could be automatic.

2. The data

2.1 Measurement methods and equipment

During the time of the field measurements in 1997-1998 there was a rather limited supply of available digital cameras at a reasonable price. The device we selected was a Canon Powershot 600 with 600*800 pixels CCD. The radiometric resolution was 8 bits per pixel on each of the RGB plains. The focal length of the objective had f=28.96 mm and the horizontal opening angle was 37.86º. With this instrument and the applied photographing distance (about 10m), the tree stems were visible roughly up to a height of 8 meters.

The camera was mounted on a tripod having fixed sight with the applied laser distance-measuring device Disto Basic (Figure 1). The tripod was balanced with a spirit level installed on the podium. The geometry of the image plane of the camera in relation to the stem was solved by attaching a reference marker stick to the front side of the each measured tree. The reference marker consisted of three white circles (d=13 cm). The width of the marker stick was 5 cm. The positions of the circles in the reference stick were known within 1 mm accuracy.

When measuring the distance from the image plane of the camera in relation to the tree to be measured, the reference stick was fastened to the tree at the required height and the distance measurement laser aimed at the middle circle of the reference stick. The photographing trigonometry was solved automatically by using a reference stick (Juujärvi et.al. (1998). In this approach the stick top is nailed to the tree so that the midpoint of the middle circle is 1.3m above the ground level with the circles pointing towards the camera. The lower and upper circles are then 0.8 m and 2.0 m above ground level, respectively. As the stick is hanging from the nail gravity keeps the stick perpendicular to the ground.

If the measurement were to be carried out without a reference marker there would be several possibilities.

The tapering estimation could be based on assumption of the position of the tree in relation to the image plane.
A special camera containing a reference system (i.e.Takahashi et.al. 1997) could be applied.
Two line lasers with known angles combined with a distance measurement laser could be installed with the camera to determine the direction of the measuring system in relation to the tree. The wavelength of the line lasers ought to be visible in all possible imaging conditions.

These simplifications would make the field work more operational because the measured tree need not be visited for fixing the reference marker. The possible errors caused by the different growth angles of the stem can be approximated trigonometrically and by simulated stem tapering (Table 1).

Table 1: The approximate volume error at the 7 m high log due to the angle of the stem in relation to the camera

Stem angle (degrees)	Volume of the log (dm^3)	Error (%)
-15	233.6	-11.1
-10	241.8	-7.4
-5	250.4	-3.6
-3	254.0	-2.2
0	259.5	0.0
3	265.2	2.1
5	269.1	3.5
10	278.9	6.9
15	289.1	10.2

Due to the obvious errors revealed by this approximation, the first alternative was rejected from further analysis. The reference marker was selected due to its simplicity. Furthermore it was expected that if the overall system would work, the third alternative or iterative version combined with comparison to the tapering function could be applied for solving the photographing geometry instead of use of the reference marker for the final system. The progress of the work would benefit if the measured trees would not have to be visited for the fixing of the reference stick.

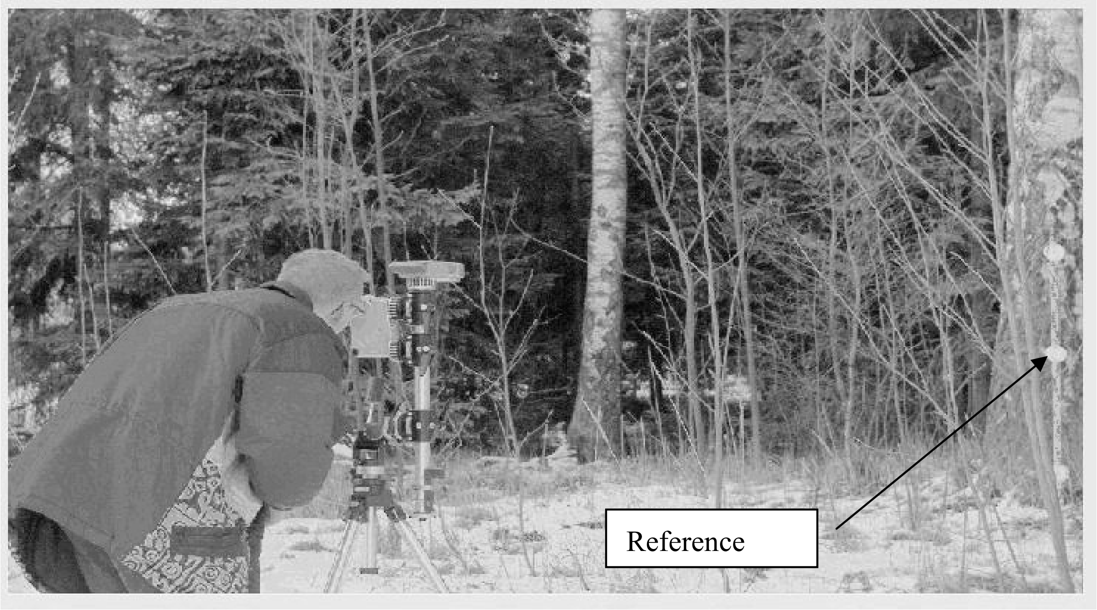

Figure 1. The measurement system in typical Finnish Forest Conditions during the first field-tests of the equipment on early spring 1997 before the actual measurement campaign.

2.2 Statistical layout of the plots and sample trees

The field plots constituted a subset of the temporary sample plots of the 9th national forest inventory of Finland (Tomppo et al. 1999, Tomppo et al. 1999). Provided the landowner gave permission to buy the sample trees and harvest them for the stem analysis plot number 7 from every 9th tract from four forestry board districts was selected for the study. Plots that did not fulfil the criteria for forestry land, as well as plots with timber production restrictions, were rejected. There were altogether 45 plots with the desired criteria of which 42 had not been clear felled after the previous national forest inventory measurements and were also accurately located in the field (figure 2).

The field work of the study took place in the summers of 1997 and 1998. In 1997, the five first pines (breast height diameters ≥5 cm) (Pinus sylvestris), spruces (Picea abies), or birches (Betula pendula or pubescens) were selected applying relascope (relascope factor 2). The counting was started from the south. In 1998, in order to avoid creating openings in the forest stand, and basing on directives of the landowners from the previous field season on how to select trees for tree analysis, every second or third suitable relascope tree was selected. In 1997, the measurements were made in Central Finland and Northern Savo. The field campaign was continued in summer on 1998 but in this work the 1988 results were applied only to check the manual field caliper measurements.

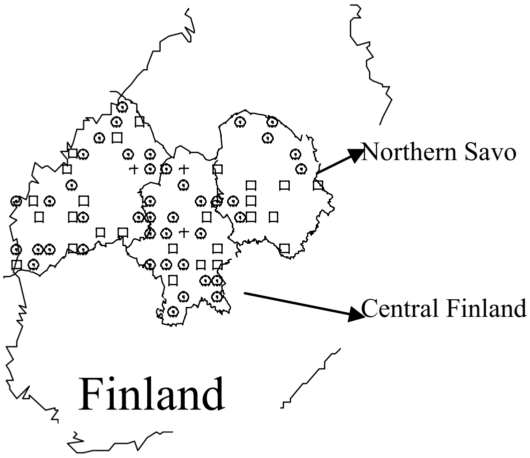

Figure 2. The locations of the sample plots are marked with a circle. The square marked plots could not be applied because the land owner did not give a permission for felling the trees. The cross marked plots had been clear felled before the field campaing.

2.3 Image data

All the trees were photographed from two directions. As closely as it practically was possible the primary direction was selected to be from South or North. This guaranteed that the manual diameter measurements will match with the photo interpretation as precisely as possible. The direction of the second photograph was ±90º from the first direction, from whichever side visibility was better. The photographs were taken from distances of 9m, 10m and 11m. The distance was measured with the Disto laser device with ± 0.5 cm accuracy. The bearing to the tree was measured with an aiming compass with 1° accuracy With these distances one pixel represented about 1 cm^2 on the photographed stem.

At first, the images were classified visually. In 20% of the cases the stems were so dark or shaded that it was impossible to get a clear image. In a further 10 %, only parts of the stem could be distinguished because trees or branches obscured the object. In the remaining picture images the most common problem was the sharp contrast in the light conditions of the background behind the tree stem that exceeded the narrow light range of the camera: when the upper parts of the stems were clearly defined against a bright sky, the lower parts merged with a dark ground.

From the remaining pictures, a great deal of the tree stems were separated between bright skies against which stem narrowing problem due to overexposure existed. In contrast to the dark ground, the light range was too narrow for detecting that part of the stem.

From a total of 650 images taken during the field season in 1997 the 143 most successful were selected for further analysis. The selected material consisted of 33 pine trees from 14 sample plots. 14 pines had been photographed from two directions, 3 from only the primary direction, i.e. the direction from or opposite the plot centre, and 16 only from the secondary direction. This was mainly due to blocking vegetation. The selected trees had to be at least 8 m high and the contours of their stems clearly visible against the background throughout the images in order to make it possible to visually estimate the stem during the development of the algorithm.

In the field data, the total number of pine trees at least 8 m high was 59 on 16 plots. Thus 56 % (33 out of 59) of the sample trees were analysed. A histogram of the distribution of breast height diameters (at 1.3 m) of all the sample trees and the sample trees whose photographs were analysed are presented in figure 3.

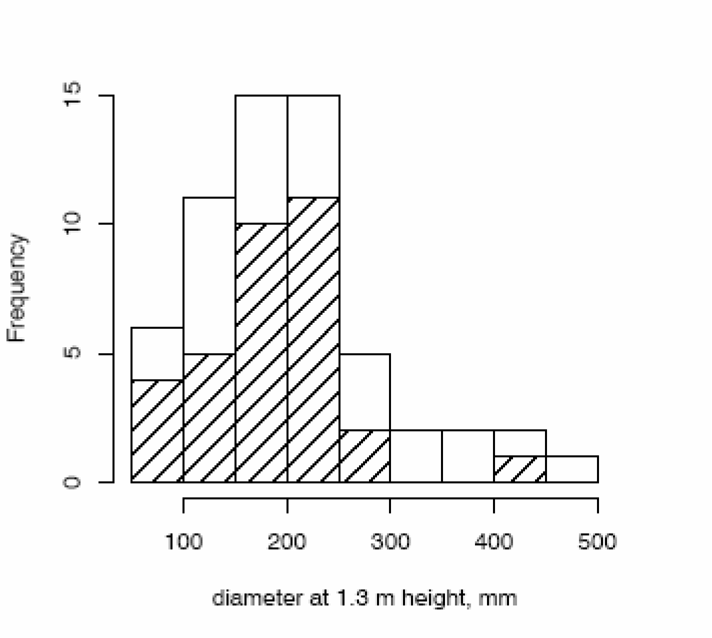

Figure 3. Frequency distribution of the breast height diameter classes (1.3 m) of all sample trees (white) and sample trees with their photographs analysed (rastered).

2.4 Field measurements on the plot

After having been photographed, the selected trees were felled. The diameters were measured twice at right angles with a caliper with 1 mm accuracy. The diameters were measured at 1.3 m and 6 m heights, at the lowest point of the living crown, and at the following relative heights of the tree: 1%, 2.5%, 5%, 7.5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 60%, 70%, 80%, 85%, 90% and 95%. All heights were measured from the ground level. In order to avoid systematic measurement errors made by different individuals, all the sample trees were measured twice by two different persons in the 1998 field season (Table 2). For this purpose, the trees were measured from the following heights: 1.3 m, 6m, and the relative heights of 2.5%, 7.5%, 15%, 30%, 50%, 70%, 85%, 90%, 95% and at the lowest point of the living crown. The material from 1998 consisted of altogether 172 felled sample trees of which 111 were pines, 36 spruces and 25 birches. Only pine trees with a minimum height of 8 m measured in 1997 were used in further analysis.

Table 2. The difference in diameter measurement results made separately by two persons

Height	Standard deviation of the difference	
	mm	%
2.5 %	6.5	3.0
7.5 %	3.0	1.7
15 %	3.1	1.9
30 %	1.9	1.3
50 %	1.8	1.5
70 %	1.0	1.3
85 %	0.9	2.0
95 %	0.9	5.0
1.3 m	4.5	2.5
6.0 m	1.4	1.2

3 The image analysis and applied tapering functions

3.1 The calibration of the digital camera

The system of lenses in a camera objective always creates distortion to the CCD plate. Due to the lenses, the photographic image is not an actual projection of the real world. When aiming for accurate measurements from the photograph, these errors have to be corrected by calibrating the camera in use. Also, the photographing geometry has to be known in each camera installation. In this study the reference stick and distance to the camera was applied. The calibration equation for the applied camera was estimated by using a 2.0 m by 3.0 m calibration plane in a laboratory (Figure 4). The aim of the calibration was to reach a 1/10000 error level that would correspond to about a calibration error of 1 mm in diameter measurement at a photographing distance of 10 m. The calibration plane consisted of filled white circles on a black background (Figure 4). The plane was produced by applying printing service, which was able to produce the exact location of all the circles on the plane. The plane was photographed from 6 different angles and the centres of the circles were detected from the images. The camera was calibrated applying Heikkilä and Silven’s (1996) lens equation with radial and tangential distortion models as described in Juujärvi et.al. (1998). The achieved accuracy was 1/26000. Consequently the calibration error does not have much importance in the tree measurement application presented at the desired level of accuracy.

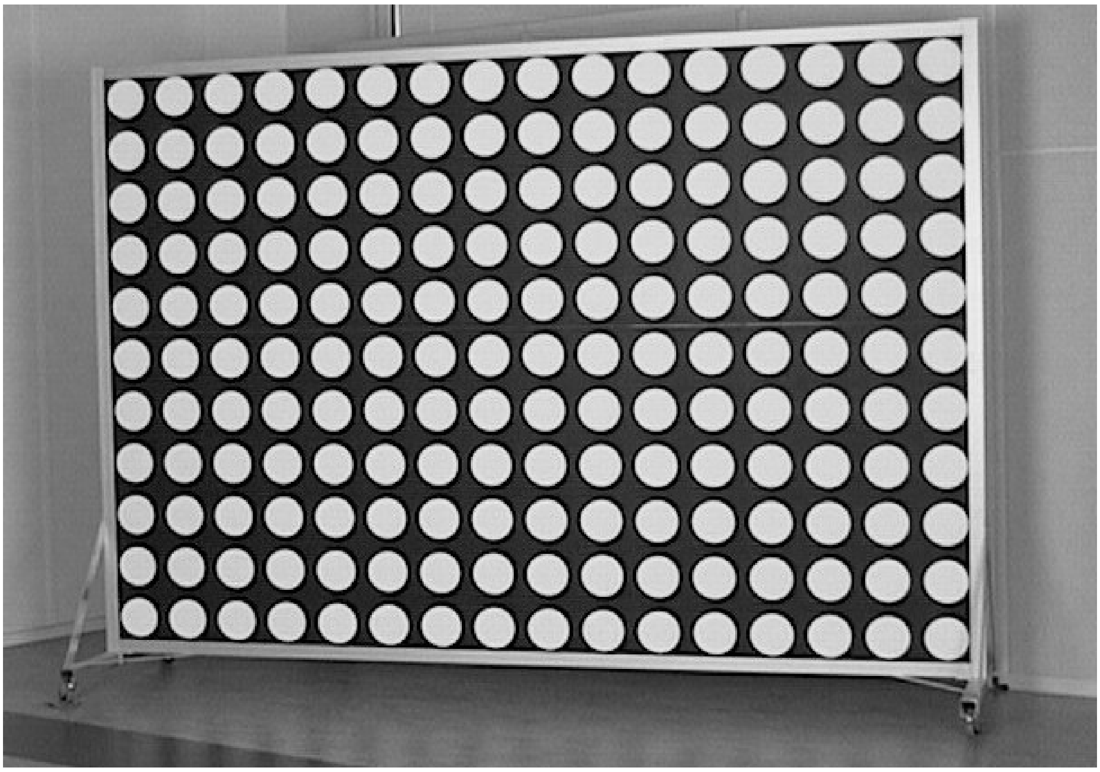

Figure 4. The calibration plane used in the camera calibration.

3.2 The tapering curve functions applied as apriori information in image analysis

A new version of the tapering model was developed for the required analysis based on the approach of Lappi (1986). In the applied tapering model, the stem is described in the polar coordinate system (Figure 5). The dimensions used to describe the stem form are the diameters corresponding to selected angle. In the first phase parameters for 12 diameters and height are estimated. In the applications of the model the same dimensions are first predicted, and the full taper curve is interpolated using cubic splines. The original model of Lappi (1986) included an artificial size parameter for each tree. However, to keep the model simple this parameter was dropped here.

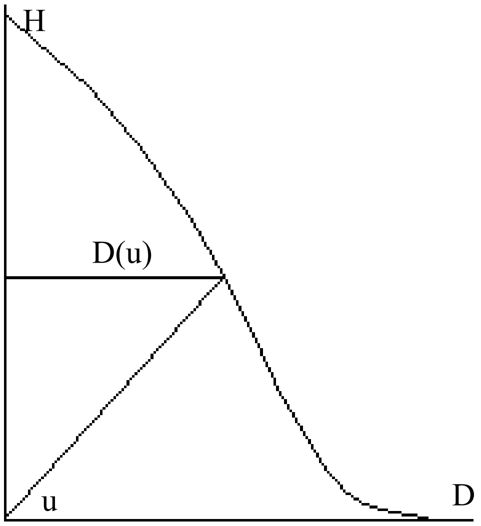

Figure 5. In the applied polar coordinate system each angle u results in the diameter D(u).

The applied model describes the diameter $D_{ki}(u)$ corresponding to the angle *u* in the tree *i* located at the stand *k* (Formula 1)

$$\log (D_{ki}(u)) = \mu(u) + b_k(u) + e_{ki}(u) \qquad (1)$$

where, $\mu(u)$ is the fixed expected value for the logarithmic diameter, $b_k(u)$ is a random stand effect of the stand, and $e_{ki}(u)$ is a random tree effect The random stand effects describe the similar tapering of the trees belonging to the same stand. The expected values of the random effects are set to zero. The stand effects and tree affects are assumed to be uncorrelated, but the stand effects of different dimensions are correlated, and similarly the tree effects are correlated. In the estimation of the model the expected values $\mu(u)$, var $(b_k(u))$, var $(e_{ki}(u))$, were estimated for each of the basic angles. The covariance $\mathrm{cov}(b_k(u_1), b_k(u_2))$ and $\mathrm{cov}(e_{ki}(u_1), e_{ki}(u_2))$ were also estimated for each of the angle pairs u_1, u_2. The parameters were estimated using the pine data collected by Laasasensaho (1982) and the estimation methods of Lappi (1986).

The estimated model can be applied for predicting the taper curve when one or more dimensions of the stem are known. In this work the field measured height and breast height diameters are applied as the known variables. The Best Linear Predictor (BLP) is used to predict unknown basic dimensions in the same way as the unknown dimensions from the multi dimensional Gaussian distributions can be predicted based on known dimensions (see e.g. McCulloch and Searle 2001).

In practice, the measurement angles do not correspond to the angles used in model estimation. For *a* given measurement angle, the expected value and variance are interpolated from fixed angles applying one dimensional cubic spline functions. The covariances were computed using two-dimensional splines. Spline subroutines of Press et al. (1992) were used. After predicting the diameters at the fixed angles, the complete stem curve is obtained using a cubic spline (Press et al. 1992).

According to the model dimensions of different trees in the same stand are correlated, and hence all measurements in a stand can be used to predict the stem curve. However, if more than one dimension is measured for a tree, the utility of measurements of other trees is limited. Thus in this study stem curves were predicted tree by tree. The covariances needed in the prediction are just sums of the corresponding covariances of stand and tree effects.

One of the advantages of the selected model is that possible measurement errors, such as diameter measurement errors (table 2), can be taken into account. If the variance of the measurement error can be estimated, the total variance of a measurement is just the sum of the variances of the tree effect, the stand effect and measurement error. If the diameter measurements do not contain measurement errors the tapering curve follows exactly the diameter measurements. If the error component exists, the tapering model corrects the measurements applying the apriori information combined with the measurements, and thus the tapering curve does not generally follow the diameter measurements.

The advantages of the applied model in the digital photo application are:

1. The tapering model can utilize any diameter measurements, which can be made from the photo
2. The selected model is able to handle the measurement errors
3. The model also produces estimates of the error variances for the results, and hence we have a probability distribution based on stem height and the breast height diameter for further image analysis
4. The tapering estimation of the tree with limited visibility and thus any few diameter measurements from the photo can be supervised applying the information of the other trees on the same stand.

BLP provides predictions, which are marginally unbiased (see e.g. McCulloch and Searle 2001). Conditionally for a given set of measurements, the predictions are unbiased only if relations between variables are linear (see e.g. McCulloch and Searle 2001). This is not exactly the case in our study. For example, the logarithmic height of the tree is clearly concave with respect to any logarithmic diameter of the lower part of the stem. As a result, the unbiased estimates can be reached only at the level of the whole population provided that estimation data is from the similar population where is it applied. This should not, however, be a serious problem in practice because there are normally several diameter measurements available from each photo. A new model, which produces better predictions than the model of this paper, has been developed more recently (Lappi 2006).

The variance component model also produces estimates of the error variances of the logarithmic diameters for every base angle. The transformation from the logarithmic diameters to absolute diameters requires the bias correction, which decreases the bias created by non-linear transformation (see Lappi 1986 for details).

3.3 The applied image analysis methodology for detecting the stem pattern

The image segmentation approach selected is based on tree segmentation combined with a priori information from the tapering model and smoothness assumption. For this purpose the image interpretation probabilities of stem diameters are combined with the probabilities produced by the tapering model via maximum posteriori approach. Here the mathematical methodology is described briefly and follows exactly the approach of Juujärvi et.al. (1998).

The stem is segmented out of the color image via the following image window based segmentation method developed for the purpose (Juujärvi et.al. 1998). Briefly, our approach estimates vertical edges for the stem in a local window (111x81 pixels), such that the colors appearing between the edges (the stem region) and out of the edges (the background region) are as distinct as possible. The algorithm searches all reasonable left and right edge combinations within the window. For each edge combinations stem and background intensity histograms are calculated and the left and right edge positions giving the best separation, i.e. when the stem and background histograms overlap as little as possible, for the stem and background segments are finally selected as the correct edge positions. By moving the segmentation window upper on the tree according to estimated previous stem edge positions, it is possible to segment the whole stem out of the image. The smoothness assumption was applied to ensure a continuous tapering curve between the analysis windows. (Juujärvi et.al. 1998).

The estimate for the tapering was obtained by combining the previously explained tapering model with image segmentation results. The tapering model was used as a priori model for the stem diameter as a function of height. This was combined with a Maximum a Posterior method (Bishop 1995) to the image segmentation probabilities to find the tapering estimate with the maximum probability. The breast height diameter and the length of the tree were used as an input for the a priori tapering model. In this case, these were given based on field measurements, but in practise they can also be approximated by image analysis in such an iterative way that first image analysis is completed without tapering model and for the second iteration the tapering model is applied by taking the known variables from the first phase. The iteration is repeated until the convergence. Estimating the diameter from each analysing window and using that as a measurement in the taper model formed the final tapering curve. For details of the image based tapering estimation algorithm, see Juujärvi et.al. (1998).

4. Results

4.1. Applicability of the imagery

The photographing conditions varied from bright sunshine to rainy moist weather. In bright sunlight the main problem with the imagery was the excessive darkening of the scenery below the horizon at the level of the forest canopy. In these conditions it was almost impossible to visually separate the stem from the background (figure 6). This was due to limited automatics in the camera for setting combinations of shutter and fader functions, and also the limited dynamic range of the CCD for such conditions. The best images from the point of image analysis were taken on cloudy days on sites with low fertility where there is naturally very little tall herb and shrub vegetation, which also disturbs the analysis. The difference from the intended photographing direction was larger than 10 degrees in 10 % of the images due to under vegetation.

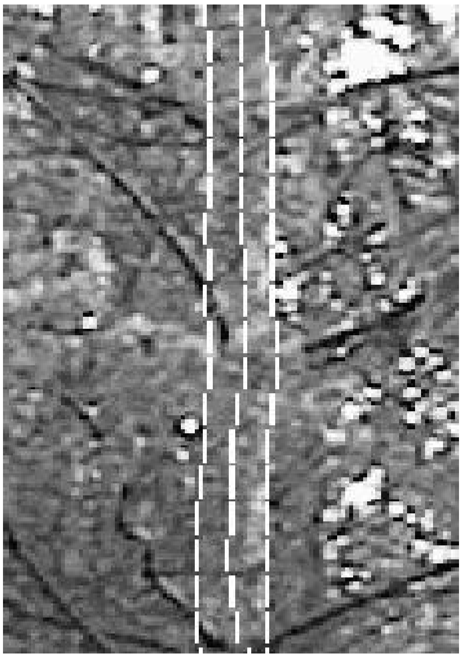

Figure 6. The stem separation in typical photographing conditions.

Around the bright objects overexposure was detected with the used CCD and thus these objects appeared larger in the pictures than in reality. In particular, the part of the stem, which was projected against the sky, looked narrower than in reality. This problem is difficult to correct mathematically because it is non-linear. It was estimated that the use of Lappi's tapering model corrected part of the error but finally it can be tackled only by applying a better optic resolution and a more dynamic CCD.

4.2 Accuracy and applicability of the tree measurements

The applied imaging method with a reference stick prevented the interpretation of the stem diameters behind the stick. This means that actually only diameters from 1.5 m up to 7-8 m heights were interpreted from the images. The differences between diameters estimated from photographs and measured from the discs in the field are presented in Figure 7. In order to avoid interpolation errors of measured diameters, the differences are calculated at the absolute heights of the field measurement.

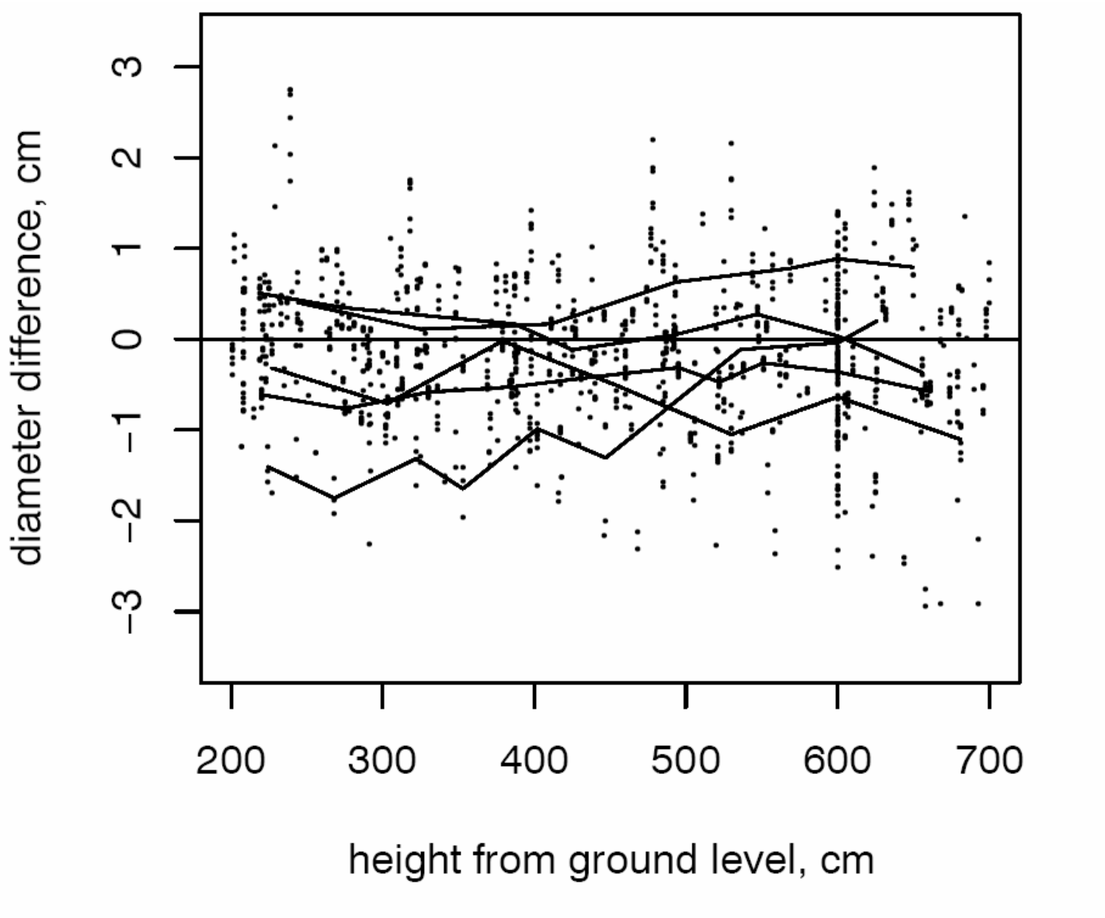

Figure 7. Differences of diameters estimated from photographs and measured from the discs. Continuous lines illustrate the differences of selected five single trees.

The diameter differences at heights 2 m - 7 m were analysed with the following variance component model (2):

$$(\text{diameter}_{\text{image}_{\text{ijkl}}} - \text{diameter}_{\text{measured}_{\text{ij}}}) = \alpha + \mathrm{a}_i + \mathrm{b}_i\sqrt{\mathrm{h}_\mathrm{i}} + \mathrm{c}_{ij} + \mathrm{p}_{ijk} + \mathrm{e}_{ijkl}, \qquad (2)$$

where $\text{diameter}_{\text{image}_{\text{ijkl}}}$ = the diameter estimated for tree i at the measurement direction j from photograph l taken at photographing position k, cm

$\text{diameter}_{\text{measured}_{\text{ij}}}$ = the field measured diameter for tree i at the measurement direction j, cm

h_i = measurement height of diameter for tree i, cm

α = mean difference between measured and estimated diameter,

$\mathrm{a}_\mathrm{i}, \mathrm{b}_i$ random tree parameters,

$\mathrm{a}_\mathrm{i} \sim \mathrm{N}\left(0, \sigma_\mathrm{a}^2\right)\forall i,\ \mathrm{b}_\mathrm{i} \sim \mathrm{N}\left(0, \sigma_\mathrm{b}^2\right)\forall i, \mathrm{cov}(\mathrm{a}_\mathrm{i}, \mathrm{b}_\mathrm{i}) = \sigma_{\mathrm{ab}}, \mathrm{cov}(\mathrm{a}_\mathrm{i}, \mathrm{b}_{\mathrm{i}'}) = 0, \forall i \neq i'$

c_ij = random effect of the measurement direction j for the tree i, $\mathrm{c}_\mathrm{ij} \sim \mathrm{N}\left(0, \sigma_\mathrm{c}^2\right)\forall i, j$,

p_ijk = random effect of the photographing position k from measurement direction j for the tree i, $\mathrm{p}_\mathrm{ijk} \sim \mathrm{N}\left(0, \sigma_\mathrm{p}^2\right)\ \forall i, j, k$,

e_ijkl = random error term, $\mathrm{e}_\mathrm{ijkl} \sim \mathrm{N}\left(0, \sigma_\mathrm{e}^2\right)\ \forall i, j, k, l$ (single photo)

The analysed photographs of a tree were taken from 1-2 directions and from each direction photographs were taken at different distances. From each location defined by direction and distance the number of analysed photographs was 1-3.The numbers of measuring heights (h) for a tree varied between 4 and 11 (between 2 m -7 m). The dependency of observations at different hierarchy levels is taken into account by random effects in the model (2). The model fit was slightly better with √h instead of h as independent variable. The model including a random plot effect was also tested, but the variance component connected with plot effect was negligible.

The parameters (Formula 2) were estimated applying SAS -Mixed procedure (SAS... 1996). The parameter estimates of the model 2 show that the tree level is dominating (table 3). The estimate of overall bias shows a statistically insignificant underestimation of 0.13 cm. The possible bias in tree tapering was tested by including $\beta\sqrt{h_i}$ into the fixed part of the model, but the estimate $\hat{\beta}$ was insignificant. For single trees, diameters estimated from photographs, may systematically under- or overestimate stem tapering, as indicated by variance component estimate $\hat{\sigma}_b^2$. Examples of this can be seen also in figure 7 where diameter differences of a set of 5 sample trees are connected with lines. The lines are not parallel, but give examples of between-tree differences in estimation errors of tree tapering. Parameter estimates $\hat{\sigma}_c^2$ and $\hat{\sigma}_p^2$ indicates that by increasing the number of photographing locations the error decreases in tree diameter estimates. The standard error of $\hat{\sigma}_c^2$ (between photographing directions) is, however, high and an inference concerning its effect would need a larger data set with trees photographed from different directions. In this data, only 16 trees had analysed photographs from two directions.

Table 3. Parameter estimates and their significance tests of model (2)

Parameter	$\hat{\alpha}$ cm	$\hat{\sigma}_a^2$.	$\hat{\sigma}_b^2$	$\hat{\sigma}_{ab}$	$\hat{\sigma}_c^2$	$\hat{\sigma}_p^2$	$\hat{\sigma}_e^2$
Estimate	-0.133	3.563	0.00925	-0.171	0.0350	0.0446	0.114
Standard Error	0.117	0.937	0.00238	0.0457	0.0247	0.0121	0.00512
Z-value	-1.14*	3.80	3.88	-3.74	1.42	3.68	22.4
Pr Z	0.262**	<0.0001	<0.0001	0.0002	0.0782	0.0001	<0.0001

*t-value and Pr< t are applied for mean difference

The accuracy of diameter estimation from the photographs was also compared with the polynomial taper curve models of Laasasenaho (1982). These models are applied also in the Finnish National Forest Inventory in estimating timber assortment proportions. Two measurement combinations in the tapering curve estimation were applied. In the first one, the estimated tapering curve was based only on height and breast height diameter and the other one was based, in addition, on the diameter at the height of 6 m. These are the combinations most commonly used in practice in Finland. The latter diameter is usually measured from the ground applying the scale at the top of a 6m long rod. This was simulated in this comparison by adding a random error component to the 6m diameters measured from the felled trees. The measurement error was assumed to be normally distributed with zero mean and standard deviation of 6 mm (Päivinen et al. 1992). Measurements of tree height and diameter at 1.3 m height were available from standing trees before felling and thus no measurement error simulation was applied for them. In estimating biases and RMSE's, the taper curve estimates of the diameters were compared with the diameters measured at direction 1, because diameters at 1.3 m height from standing trees were measured only in this direction.

The diameter estimates from the image analysis results were composed as a mean of the photograph estimates from the same tree. In estimating biases and RMSE's, the photograph estimates of the diameters were compared with the diameters measured in the photographing direction. Weighted means of measured diameters at two directions were calculated for comparisons. The weights were proportional to the number of photographs taken from each direction. The model (2) parameter estimates (table 3) indicated that an increase in the number of photographs has had some effect on the reliability. The comparisons were thus calculated both using all analysed photographs and only one (the first) analysed photograph for each tree.

In order to avoid interpolation errors in measured diameters, the taper curve and volume estimates were first derived exactly for disc measuring heights. The measuring heights between 2.5 m - 6.5 m were then classified into 1 m pieces (2.5 m - 3.5 m). The diameter bias was calculated as an average difference of tree level diameter estimates (photographs and taper curve) and disc measurements in each 1 m piece.

The root mean square errors (RMSE) in table 4 were formed according to the formula 3 (table 4).

$$RMSE = \sqrt{\sum_{i=1}^{n} (\bar{d}_{e_i} - \bar{d}_{m_i})^2 / n} \qquad (3)$$

where

$\bar{d}_{e_i}$ = average estimated diameter for tree i in 1 m pieces (2.5 m - 3.5 m, 3.5 - 4.5 m, 4.5 m - 5.5 m, 5.5 m - 6.5 m) applying image analysis or tapering function respectively,
$\bar{d}_{m_i}$ = average measured diameter for tree i in 1 m pieces,
n = number of trees.

The standard errors of image estimates are in most parts of the stem higher than those of taper curve estimates with three measured variables even if measurement error in d_6 is taken into account. The standard errors of image estimates are generally between the two taper curve models and clearly lower than those of two variable taper curve. The relatively best estimates are at 3.5 m - 4.5 m, where the accuracy is close to taper curve with three measured variables, even if the number of photographs were only 1 / tree.

Table 4. The bias (mm) and RMSE (mm) of tree diameter estimates applying image analysis and two tapering curve alternatives . $d_6^* = d_6 + e, e \sim N(0,0.6^2)$

	Image analysis		Taper model $d_h = f(d_{1.3},h)$	Taper model $d_h = f(d_{1.3}, h, d^*_6)$	Taper model $d_h = f(d_{1.3},h,d_6)$
	all photos	1 photo/tree			
All trees (n=33)					
Height 2.5-3.5 m					
- bias	-1.8	-2.8	2.8	0.7	0.6
- RMSE	7.2	8.1	7.6	6.3	4.5
Height 3.5-4.5 m					
- bias	-1.9	-2.1	3.9	0.7	0.8
- RMSE	6.9	7.3	9.4	7.2	4.5
Height 4.5-5.5 m					
- bias	-1.5	-1.5	4.3	0.2	0.3
- RMSE	8.4	9.1	10.8	7.6	4.7
Height 5.5-6.5					
- bias	-1.8	-1.7	4.6	0.1	
- RMSE	9.3	9.4	10.5	7.0	
Trees $d_{1.3}$ >16.5 cm (n=21)					
Height 2.5-3.5 m					
- bias	-0.6	-1.6	4.7	1.9	2.0
- RMSE	7.6	8.2	9.0	7.0	5.1
Height 3.5-4.5 m					
- bias	-0.6	-0.9	6.2	2.0	2.5
- RMSE	7.0	7.4	10.9	7.2	5.1
Height 4.5-5.5 m					
- bias	-1.3	-1.5	5.8	0.8	1.0
- RMSE	8.1	9.0	11.2	7.0	5.1
Height 5.5-6.5					
- bias	-1.3	-1.6	5.9	0.3	
- RMSE	8.9	9.4	10.8	6.4	

4.3 Volume estimation applying digital photo information

The image based volume estimates were compared with the volume estimates of the volume functions of Laasasenaho (1982). With the diameters estimated from the images, the best volume estimates were achieved by applying the image interpreted diameters from 2-7 m heights together with the breast height diameter and the total height as input for the above described version of the taper model of Lappi (1986). The breast height diameter and height used here were measured before felling the trees. Image estimates of diameters were taken at 1 m intervals. Estimates of standard errors were derived in connection with diameter estimation from images, but these estimates were low compared with those in tables 3 and 4 and close to the estimates for the between-person's measurement errors (table 2). For example, at heights between 4.5 m and 5.5 m the estimates of standard error were in average 1.4 mm. In volume prediction, the standard error of input diameters interpreted from images was set to 15 %, which is much higher than the estimates presented above. This is due to the dependence between errors of diameter estimates from image. When the standard errors of image estimated diameters grows in volume prediction, a high number of input diameters with correlated errors is given less weight and independently measured breast height diameter and tree height are weighted more.

The results of the comparisons are in table 5. The image based predictions were almost unbiased and in all cases better than the estimates of volume function with two measured variables. The results were at about the same level with the volume function with three measured variables assuming that d_6 is measured with error.

Table 5. The bias and RMSE of tree volume estimates applying image analysis and two volume function alternatives. Independent variables $d_{1.3}$ and h are measured from standing trees, $d_6^* = d_6 + e, e \sim N(0, 0.6^2)$, where d_6 is measured from a disc of a felled tree.

	field $d_{1.3}$, h + image ($d_{2.o}$- $d_{7.o}$)	v=f($d_{1.3}$, h) field	v=f($d_{1.3}$, h, d^*_6) field	v=f($d_{1.3}$, h, d_6) field
All trees (n=33)				
- bias, %	0.4	6.2	2.4	1.8
- RMSE, %	7.3	13.7	7.6	5.1
$d_{1.3}$ > 16,5 cm (n=21)				
- bias %	1.1	6.8	2.6	2.1
- RMSE, %	6.2	12.1	6.6	4.5

5. Discussion and the future perspectives

The calibration of the camera was very successful and seems not to set limits for the application of the single camera installation for the presented measurement approach. Another alternative would have been the use of a stereo imaging system. However, having in mind, the development of the pixel magnitude of the CCDs since the field study, it seems highly probable that a simple single camera solution can fulfil the accuracies required in forest conditions.

The most severe drawbacks of the presented installations were, as expected, the poor geometric resolution of the camera and the very limited dynamic range of the CCD. The latter resulted in dark images that had to be omitted from further analysis. However, continuously improving CCD and camera technology has at least partly overcome these problems. If the field experiment could be repeated now, the percentage of the applicable imagery could be expected to be much larger. The light leakage between pixels was a problem that was not expected but in future better equipment ought to overcome also this problem.

The achieved accuracies in the diameter and volume measurements were quite satisfactory. Image interpretations produced better diameter estimates than the two-parameter tapering curve approaches. Image based diameter estimates were relatively best at 3.5 m - 4.5 m heights, where the accuracy was close to taper curve estimates with two diameters (at 1.3 and 6 m height) and tree height as measured variables, even if the number of photographs were only 1 / tree.

The image interpreted diameters increased the accuracy of the volume estimation compared with the situation where only the breast height diameter and height were measured. The results were at about the same level as with the volume function with three measured variables assuming that d_6 is measured with error.

The applied imaging method with a reference stick prevented the interpretation of the stem diameters behind the stick. In the practical applications, the reference stick can be replaced. In practice the estimate of the pixel size can in this case be made based on the laser-measured distance from the camera to the tree and camera calibration results. This initial measurement can then be adjusted by iterating the tapering estimation and comparing the image estimated tapering with the theoretical tapering produced by the applied tapering model

Another remarkable observation is also the dependence of the interpretation accuracy and the pixel resolution of the applied camera. With the several million pixel CCDs already available, it can be expected that the results will improve. Altogether the accuracy of the camera based stem measurements can be expected to fulfil the measuring accuracy requirements for the presented applications. What is interesting is the potential usability of even rather poor cameras for forest measurement purposes. With the presented results it can be expected that even cameras such as are available in mobile phones may become useful for measurement tasks as described here.

The small quantity of the applicable images is one of the most severe drawbacks of this project. The above conclusions have to be interpreted when bearing in mind that it is expected that the trees from which the image is of good quality represents average trees in the forest. Also, with improved CCDs, it should be expected that better camera automatics will overcome the image quality problem. We did not find any common denominators, which would have shown that the trees included in the final analysis would have somehow not representative but this is always a risk with a small amount of observations.

The conclusions and future expectations should be verified applying better cameras than now available. Similarly the timber and stem quality assessment such as curviness of the stem, amount, angle, quality and thickness of the branches should be included in the analysis because these are important variables when planning the utilizations of the stem and thus in making harvesting plans. In addition, it might be possible to develop an analysis of the vitality of the analysed trees, for example, based on the visible foliar and possible symptoms of some damages such as stem damages. In addition other tree species should be included in the analysis. It can be expected that the results with other conifers would be at a comparable level. However the varying stem form and the light colour of the birch bark may make the analysis of the broadleaved species more difficult. Also the amount of the under storey affect the visibility and thus applicability of the results and this varied a lot between the trees species combinations.

Acknowledgements

The study was co-funded by Tekes, the Finnish Funding Agency for Technology and Innovation. The language of the manuscript was kindly corrected by Ms Majella Clarke and Mr Markus Hartman. We would also thank our field teams and the two anonymous referees whose comments improved the manuscript considerably.

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