LASER-BASED FIELD MEASUREMENTS IN TREE-LEVEL FOREST DATA ACQUISITION

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ABSTRACT

Remote-sensing (RS) methods, such as airborne laser scanning (ALS), are capable of acquiring tree-level forest information with high accuracy. However, these methods need more detailed reference data from sample plots than standwise mean characteristics. Field-measured treewise characteristics must be matched with ALS data on the measured position of the tree. In addition to tree position and species, diameter-at-breast height (dbh) measurements are an essential part of these reference data, since dbh at the individual tree level cannot be measured directly from the ALS data. Here we compare the accuracy in treewise field measurements with different laser-based methods in practice. The characteristics under observation include dbh, tree height and stem position. The comparable instruments used include the Terrestrial laser scanner (TLS), laser-relascope and laser-camera. The data consist of 122 trees from sample plots in Saunalahti and Nuuksio. The standard errors in dbh measurements were 8.3 mm (4.5%), 8.5 mm (4.9%) and 14.3 mm (8.3%) with the TLS, laser-camera and laser-relascope, respectively. The standard errors in positional accuracy of the tree were 0.1 m with the TLS and 0.7 m with the laser-relascope. A bias of -0.6 m (-5.2%) and standard error of 1.0 m (10.1%) were present in tree height measurements with the laser-relascope. The results of the study can be utilized e.g. in developing new cost-efficient methods for collecting ground truth data for ALS-based inventories.

1. INTRODUCTION

Treewise data acquisition from sample plots has become an essential function ever since remote-sensing (RS) methods were capable of acquiring tree-level forest data. New demands are being driven mostly by airborne laser scanning (ALS), which has been used in forest inventories in Scandinavia. Traditional forest management-planning inventories as well as coarse satellite image-based inventories have not been as dependent on plots with metre-level positional accuracy. It has been sufficient that the plot be located inside the correct stand and thus capable of describing the stand characteristics in the stratum. For more accurate satellite image- or aerial photograph-based inventories, locations of plot centre coordinates are needed, because stand characteristics are generalized to a certain number of pixels (pixel window). In traditional forest management-planning inventory, tree and plot locations are not measured. In sample plots measured for the Finnish National Forest Inventory (NFI), tree locations are determined, but are seldom utilized.
In Finland, the feature-based ALS inventory method was introduced for use in forest management planning. Stand characteristics are estimated, based on the nonparametric estimation method (Maltamo et al., 2006), which requires large numbers of reference sample plots from different stand types to function accurately. Although the method functions at the stand level, reference data are acquired at the tree level. Accurate spatial information from sample plots is needed. From the first, there has been an urgent need to develop improved field techniques for measuring tree-wise characteristics accurately, cost-effectively and reliably.

Callipers, measuring tapes and hypsometers are the most common forest sample plot measuring tools. Sampling forest plots is time-consuming and labour-intensive. Time consumption is greatly dependent on the measurer, plot size and stand structure. The advantages of traditional methods are the use of inexpensive and durable measuring devices. Tree characteristics are limited to those that are measurable at reasonable cost and accuracy with traditional measurements, such as diameter-at-breast height (dbh). Dbh is in most cases an independent variable in single tree- and stand-level models describing the growing stock. Decisions concerning forest management procedures (silviculture treatments, thinnings and final cuttings) are often made either directly or indirectly from the tree dbh measurements gathered. Actually, the interesting characteristic is the stem form, but this cannot be measured with traditional methods. A single tree's dbh or stem curve cannot be measured directly with ALS methods, but is instead estimated, based on laser-derived tree height and other information from the point cloud. ALS needs proper reference data for calibrating single-tree dbh models or estimating stand dbh-derived characteristics such as basal area.

Terrestrial laser scanning is an efficient and objective option for acquiring accurate field data. It uses the same range-finding measurement technologies as ALS to derive the three-dimensional (3D) position of objects within the scanner field of view by collecting a 3D data point cloud of several million data points in a few minutes. The applications of terrestrial laser scanner (TLS) for forestry have not been widely studied, although its potential for forest-related measurements has been more understood in recent years. The TLS method is capable of measuring all the important tree characteristics such as dbh, tree height and tree location (Hopkinson et al., 2004; Watt and Donoghue, 2005). TLS could also provide information on characteristics, such as canopy-related characteristics and stem form that have not been achievable before.

The first attempts at using conventional film cameras in measuring tree stems were already made in the 1950's (Marsh, 1952). Cameras were mainly developed to measure upper stem diameters. The measurement arrangements were cumbersome, but the accuracies achieved rather promising (Ashley and Roger, 1969; Bradshaw, 1972; Crosby et al., 1983). Development of digital cameras has eased the use of camera-based systems in field measurements, e.g. Juujärvi et al. (1998), Clark et al. (2000) and Varjo et al. (2006) have shown the feasibilities of using digital cameras in tree stem measurements. The major drawback has been that these methods have not been readily available.

Tree maps are often produced by measuring the locations of tree stems relative to the plot centre or a known point and absolute locations are calculated based on the centre point coordinates. Location determination inside the plot is traditionally done with a rangefinder and a bearing compass. Forsman and Halme (2005) mapped tree locations with two-dimensional (2D) laser observations. The method used relative positions measured with a laser that transferred to absolute positions with known points. Korpela et al. (2007) developed a method for obtaining decimetre accuracy in tree mapping that utilized combined 2D field trilateration and triangulation, using a set of known points derived by photogrammetry. RTK (real-time kinematic) is an
accurate global positioning system (GPS)-based method for measuring absolute positions to centimetre accuracy in open areas (e.g. Bilker and Kaartinen, 2001). Dense canopy often disturbs GPS measurements. In practice, it is inefficient to measure every tree position with GPS. Only the plot’s centre coordinates measurements are used. In urban environments, TLS has been capable of determining object locations to centimetre accuracy (e.g. Mechelke et al., 2007).

The aim here was to determine the practicability and accuracy of the new laser-based methods in obtaining field measurements. The tree characteristics examined were: dbh, height and location of the tree.

2. METHODS AND MATERIALS

2.1 Study area

The data for this study were collected from the Nuuksio and Saunalahti areas in Espoo, southern Finland. Six circular sample plots were measured for the study, using different methods. The plots included a total of 122 Scots pine (Pinus sylvestris), Norway spruce (Picea abies), silver birch (Betula pendula), downy birch (Betula pubescens) and other deciduous trees. The stand development classes included advanced thinning stands or mature stands under varying site conditions. The radius of the sample plot used in Nuuksio was 7.98 m and in Saunalahti 10.0 m. The sample plots in Nuuksio (3) are located in a national park and the plots in Saunalahti (3) in an urban forest. The plot coordinates were measured with the GPS RTK technique to under 10-cm precision. General information on the dbh measurements in the sample plots is presented in Table1.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>min</th>
<th>max</th>
<th>mean</th>
<th>Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scots pine (Pinus sylvestris)</td>
<td>26</td>
<td>44</td>
<td>465</td>
<td>194</td>
<td>112</td>
</tr>
<tr>
<td>Norway spruce (Picea abies)</td>
<td>52</td>
<td>54</td>
<td>265</td>
<td>137</td>
<td>58</td>
</tr>
<tr>
<td>Birch (Betula sp.)</td>
<td>25</td>
<td>50</td>
<td>404</td>
<td>225</td>
<td>91</td>
</tr>
<tr>
<td>Other deciduous</td>
<td>19</td>
<td>47</td>
<td>478</td>
<td>171</td>
<td>124</td>
</tr>
<tr>
<td>Total</td>
<td>122</td>
<td>44</td>
<td>478</td>
<td>173</td>
<td>96</td>
</tr>
</tbody>
</table>

2.2 Measurement methods and equipment

2.2.1 Traditional field measurements

In traditional measurements, tree species, dbh and tree height were determined. The values for dbh were obtained using a single measurement with steel callipers. The dbh measurements were carried out perpendicular to a line from the plot centre. The tree heights were measured using single measurements with a Haglöf Vertex clinometer (Haglöf Sweden AB, Långsele, Sweden). The Vertex is capable of measuring both heights and distances. The locations of the trees were determined with the measured bearing and distance from the plot centre. The bearing was measured with a Suunto bearing compass (Suunto Oy, Vantaa, Finland) and distance with the Vertex. All the measurement equipment was hand-held. Both bearing and distance were measured from the plot centre to the centre of the tree. Traditional measurements functioned as ground truth in the present study.
2.2.2 TLS

A Faro LS 880HE80 TLS (Faro, Lake Mary, FL, USA) was used to scan the sample plots. This device is based on light phase shift measurements with a maximum measurement speed of 120 000 points per second and laser wavelength of 785 nm, vertical field of view 320°, horizontal field of scan view 360°, beam divergence of 0.25 mrad (0.014°) and linearity error of 3 mm (at 25 m and 84% reflectivity). Only one scan per sample plot was used for manual dbh measurements on the PC screen, as described below. The scanner was stationed in or near the centre of the plot. The same measurement resolution was used for all scannings, producing a point spacing of 6 mm at distance of 10 m.

In Nuuksio the scannings were carried out in November 2007. In Saunalahti, the scannings were performed in November 2005, two growing periods prior to other measurements. The stands in Saunalahti were mature, thus, diameter growth was expected to be slow. Still this may have caused minor errors in results for the trees located there.

Faro Scene software was used for all measurements. The ground level at the tree stem was first determined in the data scanned, using a 3D view of the scanned laser points. From the ground level a height of 1.3 m was measured and marked in the intensity image. At the marked height, the intensity image was used to measure the horizontal angles to the left and right sides of the stem and the distance to the middle of the stem. These measurements were done by an operator, pointing to the side or the middle of the stem on the PC screen, and recording the angle or distance value at that point. The angles could be determined to sub pixel accuracy. These values were used to compute the radius of the tree, thus obtaining the dbh of the tree. The locations of the trees were determined, also based on horizontal angles and manual distance measurements from the intensity image.

2.2.3 Laser-camera

A laser-camera consists of a Canon EOS 400D digital reflex camera (Canon Inc., Tokyo, Japan) with an integrated Mitsubishi ML101J27 laser-line generator (Mitsubishi Electric Corp., Tokyo, Japan). The measurement of the tree dbh and the image scale determination was performed, using the length and relative position of the reflected laser line and laser point in the image. The handheld device enables the measurement of tree dbh from any desired height; in this study diameters were measured at breast height. Image interpretation was performed with specifically designed computer software in a data-processing unit. The dbh values could be measured automatically or semiautomatically. When the semiautomatic method was used, the digital images were checked in the field or afterwards. If errors were located in the digital photo, the markers that define the outline of a tree stem could be set manually. When the images were checked immediately, the data-processing unit was also used at the site. Afterwards, semiautomatic corrections were performed when the measurement errors were detected from the digital photo. The data-processing unit is planned for future integration into the camera. For a more detailed description of the laser-camera, readers are referred to Melkas et al. (2008).
2.2.4 Laser-relascope

The laser-relascope is functionally a combination of a relascope and a dendrometer. It uses distance and angle information to determine the dbh of a tree. The distance between the device and a tree is measured with a laser instrument. In addition to a laser-rangefinder, it also includes an electronic compass for determining the position of the tree (bearing and distance from the centre of a sample plot), and an electronic inclinometer is included for height measurements. For a more detailed description of the laser-relascope, readers are referred to Kalliovirta et al. (2005).

2.3 Error observation

The differences between the reference values and the values measured with different methods were calculated to determine the accuracy, i.e. both the bias and precision of the measurements. We assumed that the values measured in the reference measurements were the true values. However, all the reference measurements also included measurement errors. Therefore, the precision of the different methods was underestimated.

The measurement error for dbh was defined as

\[ e_d = d - d_0, \]

where \( d_0 \) represents the reference dbh and \( d \) the dbh measured with different methods. For the other variables (height and location), the definition was similar.

The estimate of the bias (mean error) was given by
\[ b[e_x] = e_x = \frac{1}{n} \sum_{i=1}^{n} e_{x_i} \]  

and the standard error by

\[ s[e_x] = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left( e_{x_i} - e_x \right)^2}, \]  

where \( n \) is the number of observations and \( x \) the variable considered.

3. RESULTS

3.1 Accuracy of the dbh measurements

The actual accuracy of the devices in measuring dbh was calculated from the data measured in the reference measurements with steel callipers. The most accurate method for measuring dbh was the TLS (Table 2). The laser-camera had nearly the same accuracy. Both methods had a bias of only 0.3%. The overall standard errors of the TLS and the laser-camera were 8.3 mm (4.5%) and 8.5 mm (4.9%), respectively. The laser-relascope's accuracy was relatively poor compared with these other two methods. The bias was 9.1 mm (5.2%) and the standard error was 14.3 mm (8.3%).

<table>
<thead>
<tr>
<th>Method</th>
<th>( n )</th>
<th>( b, \text{mm} )</th>
<th>( s, \text{mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLS</td>
<td>101</td>
<td>0.52</td>
<td>8.31</td>
</tr>
<tr>
<td>Laser-camera</td>
<td>120</td>
<td>0.58</td>
<td>8.51</td>
</tr>
<tr>
<td>Laser-relascope</td>
<td>119</td>
<td>9.06</td>
<td>14.33</td>
</tr>
</tbody>
</table>

3.2 Accuracy of location determination

Individual tree stem location accuracy in a sample plot was studied. The locations of the trees were determined relative (bearing and distance) from the tree's centre point to the sample plot's centre point. The reference tree location was determined with a Vertex and bearing compass. The Euclidean distances between the reference and estimated tree locations were calculated. The location error was interpreted as positive. The most accurate location determinations were with the TLS (Table 3), which showed a bias of 0.3 m and a standard error of 0.1 m, in contrast to the laser-relascope in which the bias was 1.3 m and standard error 0.7 m. The location of trees with different methods in a single sample plot is presented in Figure 2.

<table>
<thead>
<tr>
<th>Method</th>
<th>( n )</th>
<th>( b, \text{m} )</th>
<th>( s, \text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLS</td>
<td>101</td>
<td>0.27</td>
<td>0.13</td>
</tr>
<tr>
<td>Laser-relascope</td>
<td>111</td>
<td>1.34</td>
<td>0.68</td>
</tr>
</tbody>
</table>
The location accuracy determined was only relative. For absolute location accuracies, errors in plot centre coordinate determination must be taken into account. The enhanced relative location accuracy of individual trees does not necessarily ease the matching between RS and reference data, since metre-level variation may be present in location of the treetop and stump. However, the accuracies achieved with TLS should be sufficient for spatial matching of the trees. The matching algorithms must be flexible and should not require absolutely accurate coordinates as inputs. (e.g. Olofsson et al., 2008). It should also be noted that absolute accuracy of several metres may be enough for matching the reference trees to ALS-derived trees if the relative accuracy of tree locations is correct (Dorigo et al., 2008). TLS was the only method that could give information on the location of the treetop or form of the stem. The measurer can use the laser-relascope to measure the trees from the centre point, usually without changing position. Although this procedure makes measurement more flexible, metre-class errors in location accuracy may occur if measurement is not performed at the plot's centre, because the view may be obstructed to the tree. To acquire comparable reference data with the laser-relascope, the measurer must exercise caution.

![Locations determined by different methods (1-m grid)](image)

*Figure 2. Tree map from a sample plot in Saunalahti*

### 3.3 Accuracy of the height measurements

The reference heights were measured with a Vertex hypsometer. The bias in heights measured with the laser-relascope was -0.59 m (-5.2%) (Table 4) and the standard error 0.99 m (10.1%).
When tree heights are measured from the sample plot's centre with the laser-relascope, the tops of the dominant trees are seldom clearly visible and their locations must be estimated, thus incurring measurement errors.

Table 4. Accuracy of the height measurements

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>b, m</th>
<th>s, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser-relascope</td>
<td>108</td>
<td>-0.59</td>
<td>0.99</td>
</tr>
</tbody>
</table>

The TLS method is not suitable for direct tree height measurements inside the forest plot, because treetops are seldom visible behind the branches. To measure height, scanning should be done outside the plot. In a dense forest stand, the treetops may still be invisible. The laser-camera is not yet capable of performing height measurements, but the rangefinder and inclinometer from the laser-relascope can be added to it for these measurements.

4. CONCLUSIONS

The aim here was to determine the accuracy of the new laser-based methods for producing field reference measurements. In previous studies, laser technology has been used to measure stem dbh in multiple ways. The accuracy in measuring dbh varied from 8 mm to 16 mm with the laser-relascope (Kalliovirta et al., 2005) and from 8.8 mm to 14.3 mm with laser-dendrometers (Skovgaard et al., 1998; Parker and Matney, 1999). With camera-based systems the accuracies obtained have varied from 7.0 mm to 9.9 mm (Ashley and Roger 1969; Bradshaw 1972; Varjo et al., 2006) The accuracies achieved in this study were similar: 8.3 mm with the TLS, 8.5 mm with the laser-camera and 14.3 mm with the laser-relascope. Based on results in this and previous studies, the accuracies achieved in dbh measurements with laser-based methods are already at acceptable levels, considering a steel calliper's accuracy, which varies between 2.7 and 6.9 mm (Hyppönen and Roiko-Jokela, 1978; Päivinen et al., 1992).

Tree heights are difficult to measure accurately in the field when based on accurate vertical angle measurements (e.g. Vertex). The problems are related to the identification of the highest branch or foliage of a tree and to the possible horizontal offset from the tree base to the highest branch. In modern field measurements it is questionable to measure tree heights if single tree-level ALS data are on hand. Better accuracy than that achieved with ALS, ± 50 cm (e.g. Maltamo et al., 2004), is difficult to gain without using time-consuming tacheometer measurements, although only dominant trees are measurable from the ALS data and understorey tree heights must be estimated or measured. ALS-based measurements often underestimate tree heights (Rönnholm et al., 2004). In practice, it may be practical to measure certain numbers of tree heights, e.g. using hypsometers to correct for the bias in ALS-based tree height estimation.

When the target is to acquire reference data for RS, it is important that tree characteristics be matched reliably between field and RS data. If tree location is determined only with field measurements, the positional error can be metre-class due to multiple error sources (e.g. GPS, coordinates, measurement errors). When the location of the plot is determined based on RS, data matching is easier, because there are some trees whose location is already known (e.g. Korpela et al., 2007). The accuracy of location determination with TLS was 0.1 m. However, based on previous studies (Mechelke et al., 2007; Salo et al., 2008), we suggest that most of the positional error in TLS may still be derived from the field reference. In the present study, the accuracy of
location determination in the laser-relascope was 0.7 m, derived from a practical measurement mean. Without shifting position around the plot centre it is impossible to measure every tree.

If the primary interest is in classic tree and stand characteristics, the hand-held and light laser-camera would be an efficient and accurate option after combining it with functional systems from the laser-relascope. By integrating an altimeter with the laser-camera, it is possible to measure the diameter at any tree height and calculate the estimate of the dbh for every tree, using taper curves (Laasasenaho, 1982). Although TLS is a promising method, there are many problems to solve before it can be utilized for gathering reference data. TLS is an expensive measuring device and the conditions under which it can operate are limited. However, the greatest problem is that it is almost impossible to gather information on every tree during only one scanning. In the present study, 17% of the trees were omitted because they were undetectable from the scanning data. In practice, this degree of error is unacceptable in reference data. Accurate plot-level data with TLS need several scannings, which adds to the fieldwork and post processing time. Still, TLS offers boundless opportunities for the measurement of forest stands and its applications in forestry need further studies.

RS methods, such as ALS, are capable of attaining tree-level accuracy. These methods need objective and more detailed reference data from sample plots than standwise mean characteristics to exploit the method to the fullest. Laser-based field measurements need to be developed further to provide an alternative for traditional field measurements.

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5. REFERENCES


