Comparison of different Laser-based methods to measure stem diameter

Mikko Vastaranta[1], Timo Melkas[4], Markus Holopainen[1], Harri Kaartinen[2], Juha Hyyppä[2] & Hannu Hyyppä[3]

[1]University of Helsinki, Department of Forest Resource Management, Finland, mikko.vastaranta@helsinki.fi, markus.holopainen@helsinki.fi
[2]Finnish Geodetic Institute, harri.kaartinen@fgi.fi, juha.hyyppa@fgi.fi
[3]Helsinki University of Technology, Research Institute of Modeling and Measuring for the Built Environment, Finland, hannu.hyyppa@hut.fi
[4]Metsäteho Ltd, timo.melkas@metsateho.fi

Abstract

The Terrestrial Laser Scanner (TLS), the Laser-camera and the Laser-relascope were used to measure tree diameter at breast height (dbh) in boreal forest conditions. Reference diameters were measured with steel calipers, which are the most common measuring equipments for diameter. The data consisted of 122 trees from six forest sample plots in Nuuksio National Park and the Saunalahti area in southern Finland.

The results showed that the TLS and the Laser-camera are about as accurate as traditional means in diameter measurements, where as using Laser-relascope the same accuracy was not obtained. The standard errors for the TLS, Laser-camera and Laser-relascope were 8.3 mm (4.5%), 8.5 mm (4.9%) and 17.5 mm (10.1%), respectively. The bias in the TLS measurements was only 0.5 mm (0.3%) and in the Laser-camera measurements 0.6 mm (0.3%). The Laser-relascope's bias was overall 9.1 mm (5.2%).

The TLS and Laser-camera were determined to be accurate methods of measuring dbh. These methods also enable the measurement of other characteristics, such as diameters at multiple heights, which can improve volume or tree quality estimates. These possibilities need further research.

Keywords: Forest mensuration; stem diameter; accuracy; Terrestrial Laser Scanning; laser

1 Introduction

The most important variable in forest management planning at a single tree level is stem diameter at breast height (dbh). With dbh, tree height and tree species, all the important stand characteristics, such as growing stock and basal area, can be estimated. Forest management planning will increasingly utilize more remote sensing methods due to their improved cost-efficiency and the enhanced accuracy of some new remote sensing methods, such as airborne laser scanning (ALS). In Finland, the accuracy of the stand characteristics estimated by ALS is as accurate as the stand characteristics assessed by the traditional ocular field inventory (Suvanto et al. 2005). Still, a single tree's dbh cannot be measured directly by ALS data and is estimated based on laser-derived tree height and other laser information, such as crown size. Such estimates needs proper reference data to decrease the bias in it. Thus, there is also need to develop improved field techniques to measure stem diameters and stem volume cost-effectively and reliably.

Traditional means of field measurements are labour intensive and time consuming. Additional measurements, such as diameter measurements from multiple heights, would enhance the accuracy of volume estimation in preharvest measurements or of modelling growth in forest management planning, but such additional field measurements have in practise been limited due to a lack of efficient means. There are also many other exploitable stand or tree characteristics, where there exist no effective traditional means to measure. These characteristics include e.g. biomass, leaf area, crown characteristics or quality of stem. The development of field measuring devices has not been very intensive in recent years, although there have been some attempts to develop and test new efficient and easier to use devices for forest measurements (e.g. Carr 1992; Carr 1996; Williams et al. 1999; Kalliovirta et al. 2005; Varjo et al. 2006), but these new devices are not yet widely used. Developed new devices have been inaccurate, expensive or hard to use in the field. The reasons for the slow development of easy-to-use field measurements are e.g. variable forest environments, which are challenging for all measuring devices, and a limited market. Field measuring devices in the future must be precise, quick, user friendly and water- and shockproof. Furthermore, the device should enable the efficient measurement of all the basic tree characteristics from the centre of a sample plot, and the price of the device should be reasonable (Kalliovirta et al. 2005).

As stated earlier, there is an urgent need for development of new, terrestrial remote sensing-based techniques, which can produce diameter-type information not achievable by means of airborne remote sensing. Such new methods should be preferably more cost-efficient and accurate than traditional field measurements. New laser-based techniques have showed some promises for that kind of use (e.g. Danson et al. 2007; Hopkinson et al. 2004; Watt and Donoghue 2004; Kalliovirta et al. 2005). Terrestrial laser scanning is an efficient and objective option to collect accurate field data. It uses the same range-finding measurement technologies as ALS to derive the 3D position of objects within the scanner field of view by collecting 3D data clouds of several million data points in a few minutes. Applications of terrestrial laser scanning for forestry have not been widely studied, although its potential for forest related measurements have been more understood in recent years. Watt and Donoghue (2005) scanned two forest sample plots with a terrestrial laser scanner (TLS) and compared the results to field measurements. The results demonstrated that accurate measurements of tree diameters can be derived directly from the laser scan point cloud return in instances where the sensor's view of the tree is not obstructed. Hopkinson et al. (2004) also accurately measured stem location, tree height and density from the TLS data. Danson et al. (2007) studied with promising results how the forest canopy gap fraction could be determined with TLS. Canopy-related characteristics have been hard to measure by other means.

Kalliovirta et al. (2005) used a Laser-relascope, which was also used in this study, to measure tree diameter, height and location. They reported the Laser-relascope's standard error for tree diameter, height, and position of 8.2 mm, 49 cm and 32 cm. Although the Laser-relascope was accurate enough, the results were observer-dependent and the most time-consuming part of the measurements was the diameter measurement. Juujärvi et al. (1998) and Varjo et al. (2006) have studied digital cameras (Canon PowerShot) applicability for measurement of stem diameter from different heights. They developed a method where a laser-rangefinder, digital photograph and calibration stick were used to determine stem diameter for the desired height of the stem. Interpretation of the digital photograph was controlled with taper curve models (Lappi 1986). The accuracy of stem diameter determination varied from 7.0 to 9.4 mm (RMSE) with a bias of 0.6-2.8 mm. The height of the measurements varied from 2.5 to 6.5 meters.

This study concentrates on the accuracy of measuring stem diameters by different means, because of the importance of that variable in forest management planning and calibration of ALS-based estimates. Stem diameters were measured by four different methods: By 1) TLS, 2)

Laser-camera, 3) Laser-relascope and for reference by 4) traditional means with steel calipers. The aim of this study was to test the new measuring devices in typical forest conditions. The accuracy (i.e. bias and precision) of the diameter estimates were examined.

2. Methods and materials

2.1 Study area

The data for this study were collected from the Nuuksio and Saunalahti areas in Espoo in southern Finland. Six circular sample plots were measured for the study by different means. The plots included altogether 122 Scots pines (P. sylvestris), Norway spruces (P. abies), birches (B. pendula and B. pubescens) and other deciduous trees. The stand development classes were advanced thinning stands or mature stands and site conditions varied from grove-like moor to rocky cliff top. The radius of 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) are in an urban forest. The variation in tree level in one plot was obviously more diverse than in economically managed forests in Finland, because the stands were uneven-aged. The reference measurements in the study areas were carried out in fall 2007 and winter 2008. General information about the diameter measurements in the sample plots is presented in table 1.

Table 1. General information about the diameter measurements (mm). Measured with reference device, steel caliper.

	N	min	max	mean	s.d.
Pine	26	44	465	194	112
Spruce	52	54	265	137	58
Birch	25	50	404	225	91
Other deciduous	19	47	478	171	124
Total	122	44	478	173	96

2.2 Measurement methods and equipment

2.2.1 Reference measurements

The traditional measurements, which were used as reference, included all the plots general information, such as forest site conditions and the stand's development class. In the traditional measurements, tree species and diameter at breast height (dbh) was determined. Dbh was measured using a steel caliper, and the breast height was marked on the tree. The measurements were always carried out from the same direction of the trees to minimize unwanted error sources.

2.2.2 Terrestrial Laser Scanner

A Faro 880HE80 TLS was used to scan the sample plots. FARO LS 880 HE80 is based on phase measurements with maximum measurement speed of 120000 points/sec, 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. 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 the distance a 10 metres.

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

Faro Scene software was used for all measurements. First the ground level at the tree stem was determined in the scanned data by using a 3D-view of the scanned laser points (Figure 1, left). From the ground level a height of 1.3 metres was measured and marked in the intensity image (Figure 1, right). At the marked height, the intensity image was used to measure the horizontal angles to the left and right side of the stem and the distance to the middle of the stem. These values were used to compute the radius of the tree, thus obtaining the dbh of the tree.

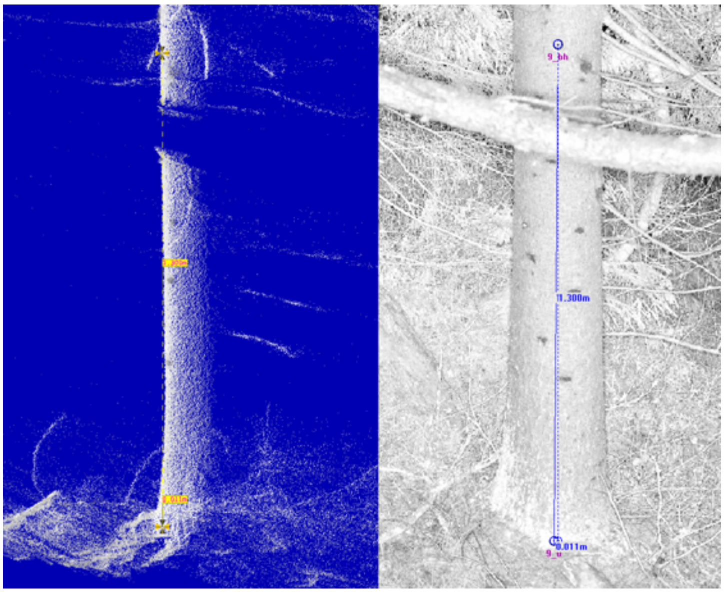

Figure 1. Scanned laser points of one tree stem, side view on the left, intensity image on the right. Ground level and 1.3 metre height are shown on both images.

2.2.3 Laser-camera

A Laser-camera consists of a Canon EOS 400D digital reflex camera with an integrated Mitsubishi ML101J27 laser line generator. The measurement of the tree diameter is performed by using the length and relative position of the laser line on the image. The method is developed by Ojanen (2005). The device enables the measurement of tree diameter from any desired height, in this study diameters were measured at dbh. Image interpretation was performed with specifically designed computer software in a data processing unit. The diameters could be measured automatically or semi-automatically. When using the semi-automatic method, digital images were checked in the field or afterwards. If errors are located in the digital photo, the markers that define the outline of a tree stem can be set manually. When images were checked immediately, the data processing unit was also used at the site. Afterwards, semi-automatic corrections were made when measurement errors were detectable from the digital photo. In future, the data processing unit is planned to be integrated into the camera. For a more detailed description of the Laser-camera, readers are referred to Kivilähde (2008) or 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 diameter 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 Calculating the accuracy of diameter measurements

Plot measurements taken by traditional means were used as a reference. The differences between the reference values and the values measured with different means were calculated to examine the accuracy, i.e. both the bias and precision of the measurements. The first assumption was that the values measured in reference measurements were the true values. However, all the reference measurements with steel calipers also include measurement errors. For purpose of comparison, those errors were taken into account by using information from previous studies (Hyppönen and Roiko-Jokela 1978; Päivinen et al. 1992). Previously reported standard errors were used as the standard errors for the reference methods when estimating the accuracy of different methods. If it is not mentioned separately that steel caliper errors have been taken into account, the reference measurements are assumed to be correct. Student's paired t-test was used to test were the diameters measured by different means were statistically different from one another.

The diameter measurement error for different measurements was defined as

$$e\_d = d - d_0, \tag{1}$$

where d_0 represents the reference diameter and d the diameter measured with different means.

The reliability of the measurements was examined with the estimation of mean square error (MSE). Because the true values of the variables were assumed to be known, the MSE can be divided into the variance and the square of the bias (Cochran, 1977). The estimate of the bias (mean error) was given by

$$b[e\_x] = e\_\bar{x} = \frac{1}{n}\sum_{i=1}^{n} e\_x_i \tag{2}$$

and the standard error was given by

$$s[e\_x] = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left[e\_x_i - e\_\bar{x}\right]^2}, \tag{3}$$

where n is the number of observations and x is the diameter (measured by the reference and the method under observation).

When calculating standard errors for different methods and the measurement errors are independent, the standard error of reference method can be taken into account as follows:

$$s[e\_x]_{method} = \sqrt{s[e\_x]^2 - s[e\_x]^2_{reference}} \tag{4}$$

where $s[e\_x]_{reference}$ is the standard error for steel calipers.

3. Results

The precision and bias of diameter measurements were studied. The actual accuracy of the devices in measuring dbh was calculated from the data measured in the reference measurements with a steel caliper. The most accurate method of measuring dbh was the TLS (Table 2; Figure 2). The Laser-camera had nearly the same accuracy. Both methods had a bias of only 0.3%. The overall standard errors of TLS and the Laser-camera were 8.3 mm (4.5%) and 8.5 mm (4.9%), respectively. The accuracy (standard error) of steel calipers is reported to vary between 2.7 mm and 6.9 mm (Hyppönen and Roiko-Jokela 1978; Päivinen et al. 1992). The standard error calculations for TLS and the Laser-camera taking the standard errors of steel calipers into account enhances the accuracy of these two methods. In our calculations, the standard errors for TLS varied from 4.6 mm (2.5%) to 7.9 mm (4.2%) and for the Laser-camera from 5.0 mm (2.9%) to 8.1 mm (4.7%). Student's paired t-test was used to test were the diameters measured by different means were statistically different from one another. It revealed that there were no statistically significant differences between the reference method and the TLS (t=0.56) or the reference method and the Laser-camera (t=0.75). Differences in measurements between reference method and Laser-relascope were significant (t=5.65). On the basis of these results, we can state that in practice TLS and the Laser-camera are as accurate as the reference method.

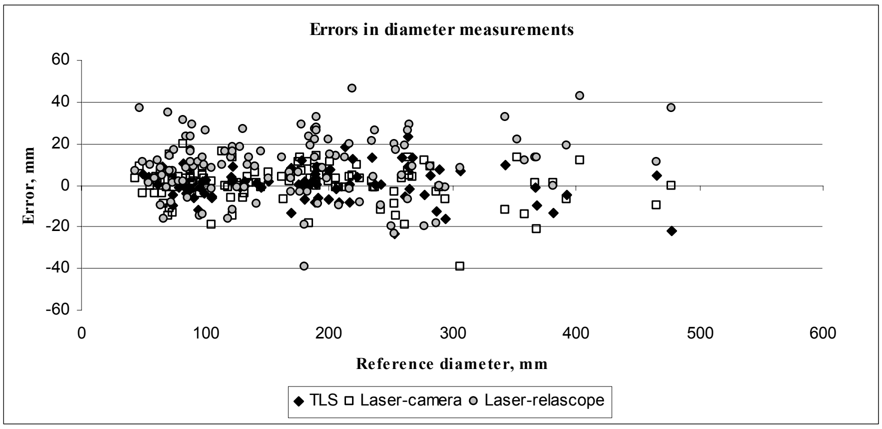

Figure 2. Errors in the diameter measurements with different means.

Table 2. Accuracies of diameter measurements (mm), bias and standard error proportioned to the mean diameter in parenthesis.

Method	n	bias	S_E	S_E*	S_E**
TLS	82	0.52 (0.28)	8.31 (4.46)	7.86 (4.21)	4.64 (2.49)
Laser-camera	120	0.58 (0.34)	8.51 (4.94)	8.09 (4.69)	5.02 (2.91)
Laser-relascope	119	9.06 (5.24)	17.49 (10.11)	17.28 (9.99)	16.07 (9.29)

*S_E without steel calipers S_E as reported in Hyppönen and Roiko-Jokela 1978 (2.7 mm).
**S_E without steel calipers S_E as reported in Päivinen et al. 1992 (6.9 mm).

The Laser-relascope's accuracy was relatively poor compared to these other two methods. The bias was 9.1 mm (5.2%) and the standard error was 17.5 mm (10.1%), varying by 16.1-17.3 mm (9.3-10.0%) if the standard error for steel calipers is taken into account. Kalliovirta et al. (2005) have reported a standard error of 8.2 mm for the Laser-relascope and variation with it among measurers (8.0-16.1 mm). Those results show that the accuracy of this method is really dependent on the measurer. The Laser-camera, which is actually an improved version of the Laser-relascope, is easy to use and does not need such an experienced measurer. Kalliovirta et al. (2005) also noticed that a diameter measurement with the Laser-relascope is not easy enough to use in actual field work and the measurements are subjective. Those were main reasons to start the development of the Laser-camera.

The accuracy of measuring the three main tree species in Finland, pine, spruce and birch, vary slightly between the methods (Table 3). The variation in accuracy for the three main tree species was with TLS 6.1-9.8 mm, with the Laser-camera 8.2-10.5 mm and with Laser-relascope 16.4-20.6 mm. With TLS or the Laser-camera all the main tree species were measured accurately enough for practical use. What is most important is to obtain observations from every tree in a sample plot with these methods. For some reason deciduous trees (birches and other deciduous) were measured the most inaccurately in this study, although, with laser-based methods, it is easily assumed that trees with many under story branches, such as spruces, would be the most inaccurate to measure. One guideline for all of these laser-based methods is that visibility to the stem must be clear.

Table 3. The Accuracy of diameter measurements (mm) by tree species, bias and standard error proportioned to the mean diameter in parenthesis.

Method	n	bias	S_E
TLS			
Pine	16	0.11 (0.05)	6.14 (2.88)
Spruce	35	3.07 (2.08)	7.64 (5.18)
Birch	21	0.20 (0.09)	9.78 (4.53)
Other deciduous	10	-7.08 (-3.21)	11.23 (5.09)
Laser-camera			
Pine	26	0.96 (0.49)	8.26 (4.25)
Spruce	51	0.94 (0.68)	8.16 (5.92)
Birch	25	-0.44 (-0.20)	10.45 (4.64)
Other deciduous	18	0.44 (0.27)	7.72 (4.62)
Laser-relascope			
Pine	26	10.81 (5.44)	16.36 (8.24)
Spruce	47	8.53 (6.47)	16.37 (12.42)
Birch	25	8.44 (3.75)	20.56 (9.14)
Other deciduous	21	8.81 (5.13)	18.60 (10.83)

4. Discussion

In this study new measuring devices were tested in forest conditions. The accuracy (i.e. bias and precision) of diameter measurements were examined. Based on this study, it seems that with new laser-based methods, TLS and the Laser-camera, stem diameter can be measured as accurate as it is measured in traditional field measurements with steel calipers. This study concentrated on stem diameter measuring accuracy, because of the importance of that variable in forest management planning and calibration of ALS-based estimates. The accuracy of the measurements of other variables need further studies.

TLS measurements in Saunalahti's three plots were completed in 2005 (two growth periods ago). This may cause bias in the TLS results for those plots, although the stands were mature, thus, the diameter growth is expected to be slow. All the other measurements were performed in 2007. It was impossible to get an observation from every tree in a plot with the TLS, because there was only one scan per plot. That problem should be fixed with more scannings per plot before accurate plot level estimates could be calculated. If several scannings are needed, it will add the amount of field work and post-processing notably.

Traditional methods are labour intensive and time consuming. Steel calipers can provide accurate diameter measurements and a useful reference data, but now it can be noted that there are other similarly accurate options with a wide range of other possibilities that traditional measurements do not offer, e.g. the measurement of diameters at multiple heights, which would improve volume estimates and give valuable information about tree quality. The Laser-camera's principle for diameter measurement has been significantly improved from its previous prototype, the Laser-relascope. Laser-relascope's functionalities besides measuring diameter - including measuring tree heights and producing tree maps - made the device promising itself, but Laser-camera's principle for diameter measurements is a major improvement and should be added on to it. The Laser-camera has given promising results and, thus, should be developed further together with the Laser-relascope. The price of the Laser-camera would be on a totally different scale than the price of an expensive TLS.

In earlier studies laser technology has been used to measure stem diameter in multiple ways. The accuracy of measuring diameters have varied from 8 mm to 16 mm with 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 a camera-based system Varjo et al. (2006) obtained an accuracy varying from 7.0 mm to 9.4 mm. Achieved accuracies in this study are within the same level, 8.3 mm with TLS, 8.5 mm with Laser-camera and 17.28 mm with Laser-relascope. Laser-camera was in first test under forest conditions in this study and in the study of Melkas et al. (2008). When Ojanen (2005) developed Laser-camera's measuring method, the aim was to create a method that is able to measure stem diameter with an accuracy of +-5 mm. Results from this study are promising for Laser-camera, although such level of accuracy was not quite achieved.

Based on results in this and earlier studies, it can be noted that the achieved accuracies with laser-based methods are already in acceptable levels considering steel caliper's accuracy, which is reported to vary between 2.7 and 6.9 mm (Hyppönen and Roiko-Jokela 1978; Päivinen et al 1992). In this kind of comparison studies, results obtained by using steel caliper are often taken as an absolutely truth. With laser-based measuring methods, it is more important to concentrate on developing these new methods that can be used in daily field work and help to automatize measured data's possible post-processing.

TLS and the Laser-camera can both provide new and useful methods for producing accurate diameter measurements for reference data for research and forest inventories on different scales. The Laser-camera is easy to use, the price would be reasonable, and the diameter measurements are accurate. If the primary interest is classic stand characteristics, the Laser-camera would be an efficient and accurate option after other functionalities from the Laser-relascope have been added to it. On the other hand, TLS gives totally new possibilities for the measurement of forest stands. Although this study only compared the diameter measurements, TLS can provide a wide range of objective measurements of different stand characteristics (e.g. Hopkinson et al. 2004; Watt and Donoghue 2005; Henning and Radtke 2006; Danson et al. 2007). The TLS method does not depend on plot size, and larger plots or whole stands could also be measured at a reasonable cost, which has been almost impossible with traditional means. TLS applications in forestry need further studies.

In general, there is a need for devices that make forest field inventory easier. New laser-based methods are promising for this. Still, further studies are needed in order to develop these methods to be able to displace traditional methods in practical work.

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