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Feasibility of Terrestrial Laser Scanning for Plotwise Forest Inventories

by

Xinlian Liang

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Abstract

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Abstract

Detailed, up-to-date forest information is increasingly important in quantitative forest inventories. The accuracy of the information retrieval is highly dependent on the quality and quantity of the reference data collected on field sample plots. In practice, the plotwise forest data are used as a reference for the calibration of large-area inventory data measured by aerial and space-borne remote sensing techniques. Field reference data are conventionally collected at the sample plot level by manual measurements. Because of the high costs and labor intensity of manual measurements, the number of tree attributes collected is limited. Some of the most important tree attributes are not even measured or sampled.

Terrestrial laser scanning (TLS) has been recently shown to be a promising technique for forest-related studies. Many tree attributes have been correlated with measurements from TLS data. Numerous TLS methods have been proposed. However, the feasibility of applying TLS in plotwise forest inventories is still unclear. The major missing factor is automation of data processing. Other factors hampering the acceptance of the technology include the relatively high cost of the TLS instrument, the low measurement accuracy achieved using the automated data processing currently available, and the shortage of experimental results related to the retrieval of advanced stem attributes (e.g., stem curve) and to different forest conditions.

In this study, a series of methods to map sample plots were developed, and their applicability in plotwise forest inventories was analyzed. The accuracy of stem mapping, the efficiency of data collection, and the limitations of the techniques were discussed. The results indicate that TLS is capable of documenting a forest sample plot in detail and that automated mapping methods yield accurate measurements of the most important tree attributes, such as diameter at breast height and stem curve. The fully-automated TLS data processing that was developed in this study resulted in measurement accuracy similar to that of manual measurements using conventional tools or models and of manual measurements from point cloud data. The results of this study support the feasibility of TLS for practical forest field inventories.

Further research is needed to explore new protocols for the application of TLS in field inventories. Three possible new directions are the integration of detailed tree attributes (e.g., stem curve, volume, and biomass) in large-area inventories, the utilization of TLS field plots in national forest inventories, and the mapping of large sample plots, e.g., in operational harvest planning. More studies need to be performed on sample plots under different forest conditions (development class, tree species, and amount of ground vegetation).

Keywords terrestrial laser scanning, forest inventories, stem curve, volume, biomass, change detection

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Tiivistelmä

Tarkka ja ajantasainen metsävaratieto on yhä tärkeämpää metsätaloudessa. Laajojen metsäalueiden inventointi ja seuranta perustuu maastomittauksiin ja kaukokartoitustulkintaan. Maastossa mitattuja koealoja hyödynnetään kaukokartoituksen referenssi- tai kalibrointiaineistoina. Tällöin tulkinnassa käytettävien referenssi- tai kalibrointikoealojen mittaustarkkuus on ratkaisevan tärkeää. Perinteisesti maastoreferenssi on kerätty koealoilta manuaalisilla mittauksilla, mikä on työlästä. Korkeiden työvoimakustannusten vuoksi mitattavien puutunnusten määrä on rajallinen, ja joitakin tärkeitä puutunnuksia ei voida operatiivisesti edes mitata.

Maastolaserkeilaus (Terrestrial Laser Scanning, TLS) on viime aikoina antanut lupauksia puiden mittaamiseen. Monet puutunnukset korreloivat hyvin TLS-piirteiden kanssa, ja useita menetelmiä puiden mittaukseen on esitetty. TLS:n soveltuvuus koealoihin perustuvaan metsävarojen inventointiin on kuitenkin edelleen epäselvää. Suurin ongelma on TLS-aineiston automaattinen käsittely ja tulkinta. Muita uuden tekniikan käyttöönottoa rajoittavia tekijöitä ovat TLS-laitteiston suhteellisen korkea hinta, tarjolla olevien automaattisten menetelmien huonot mittaustarkkuudet sekä käytännön testien puuttuminen (esim. runkokäyrän mittaus) erilaisissa puustoissa ja metsiköissä.

Tutkimuksessa kehitettiin useita TLS-menetelmiä koealojen kartoitukseen ja mittaukseen. Lisäksi menetelmien soveltuvuutta koealoihin perustuvassa metsävarojen inventoinnissa analysoitiin ottaen huomioon runkojen paikannuksen tarkkuus, aineiston keruun tehokkuus sekä tekniikan rajoitukset.

Tulosten mukaan TLS-mittaukset ovat soveltuvia metsikkökoealan tarkkaan kartoitukseen ja automaattiset menetelmät tuottivat tarkkoja mittaustuloksia tärkeimmistä puutunnuksista, kuten puiden rinnankorkeusläpimitasta ja runkokäyrästä. Täysin automaattinen TLS-aineiston käsittelymenetelmä, joka tutkimuksessa kehitettiin, tuotti samantasoista mittaustarkkuutta kuin perinteiset metsässä tehtävät mittausmenetelmät tai TLS-pistepilvestä suoritetut manuaaliset mittaukset. Tulokset osoittavat TLS-mittausten olevan potentiaalinen menetelmä operatiiviseen metsävarojen maastoinventointiin.

Jatkotutkimuksia tarvitaan operatiivisen TLS-inventointimenetelmän kehittämiseen. Kolme mahdollista tutkimuslinjaa ovat TLS:llä mitattujen tarkkojen puutunnusten (esim. runkokäyrä, tilavuus ja biomassa) integrointi laajojen alueiden inventointeihin, TLS-koealojen hyödyntäminen operatiivisessa valtakunnan metsien inventoinnissa (VMI) sekä laajojen koealojen mittaaminen TLS:llä, esimerkiksi operatiivisen leimikkosuunnittelun yhteydessä. Lisäksi tarvitaan edelleen jatkotutkimuksia TLS-mittausten tarkkuudesta erilaisissa metsiköissä (kehitysluokka, puulaji, aluskasvillisuuden määrä).

Avainsanat maastolaserkeilaus (maalaserkeilaus), metsien inventointi, runkokäyrä, tilavuus, biomassa, muutostulkinta

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PREFACE

The study presented in this thesis was carried out as part of my work as a researcher at the Finnish Geodetic Institute (FGI), Department of Remote Sensing and Photogrammetry. I hope that this collection of work provides a new starting point and source of motivation for further research and development of algorithms and procedures for efficient forest inventory and management.

I am thankful to many people who have been supporting me in this study. I would like to thank the supervisor of this thesis, Professor Henrik Haggrén from Aalto University, Department of Real Estate, Planning and Geoinformatics. The discussions we had, especially the ones at the beginning and at the end of this study, gave me many constructive suggestions. It has been a great experience to share his insightful understanding of postgraduate studies. I would like to thank Prof. Juha Hyyppä from FGI. His firm support for this study was indispensible to this work. The great success achieved in the department under his leadership provides young researchers an example of a distinguished academic career. It is my honor to work with him. I would like to thank Professor Markus Holopainen from University of Helsinki for his continuous support and advice. We have shared a lot of great ideas in meetings, conferences, and papers.

Several other people have also contributed to this study, and I would like to express my gratitude to all of them. The co-authors of the appended papers, Paula Litkey, Harri Kaartinen, Antero Kukko, Xiaowei Yu, Mikko Vastaranta, Ville Kankare, and Timo Melkas had important roles in this study. The staff of our department and of the entire FGI—Professor Risto Kuittinen, Professor Ruizhi Chen, and Päivi Sarin to name just a few—have helped me in many ways during the work. I will not list everyone here, but you all have my great respect.

I would like to thank the pre-examiners of my thesis, Professor Barbara Koch, University of Freiburg, Freiburg, Germany, and Professor Randolph Wynne, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A. It is a privilege to have this thesis evaluated by such well-respected pioneers in the field of laser-scanning-based forest inventory. I would also like thank the anonymous reviewers of the appended papers for their valuable comments on the study.

Finally, special thanks are reserved to my family and friends for their great support throughout my study and work.

Kirkkonummi, 19 August 2013
Xinlian Liang

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LIST OF PUBLICATIONS

The thesis is based on the following publications, referred to in the text by their Roman numerals:

I. **Liang, X.**, Litkey, P., Hyyppä, J., Kaartinen, H., Vastaranta, M., Holopainen, M., 2012. Automatic stem mapping using single-scan terrestrial laser scanning. *IEEE Transactions on Geoscience and Remote Sensing*, 50(2): 661–670.

II. **Liang, X.**, Litkey, P., Hyyppä, J., Kaartinen, H., Kukko, A., Holopainen, M., 2011. Automatic plot-wise tree location mapping using single-scan terrestrial laser scanning. *The Photogrammetric Journal of Finland*, 22(2): 37–48.

III. **Liang, X.**, Hyyppä, J., 2013. Automatic stem mapping by merging several terrestrial laser scans at the feature and decision levels. *Sensors*, 13(2): 1614–1634.

IV. **Liang, X.**, Kankare, V., Yu, X., Hyyppä, J., Holopainen, M. Automated stem curve measurement using terrestrial laser scanning. *IEEE Transactions on Geoscience and Remote Sensing*, DOI 10.1109/TGRS.2013.2253783.

V. Yu, X., **Liang, X.**, Hyyppä, J., Kankare, V., Vastaranta, M., Holopainen, M., 2013. Stem biomass estimation based on stem reconstruction from terrestrial laser scanning point clouds. *Remote Sensing Letters*, 4(4): 344-353.

VI. **Liang, X.**, Hyyppä, J., Kaartinen, H., Holopainen, M., Melkas, T., 2012. Detecting changes in forest structure over time with bi-temporal terrestrial laser scanning data. *ISPRS International Journal of Geo-Information*, 1(3): 242-255.

All of six publications are original papers, which are peer reviewed journal articles in academic journals.

The author's contribution

In **I**, I developed the concept and method, carried out the tests and analyses, and wrote the paper. Paula Litkey supported the work throughout the paper writing. Juha Hyyppä was the advisor in the study. Harri Kaartinen made the field surveys. Mikko Vastaranta provided the field reference data. Markus Holopainen was the advisor on forest inventories.

In **II**, I developed the concept and detecting method, and wrote the paper. Paula Litkey developed the filtering and modeling method, wrote Section 2.4 and 2.5. The tests and analyses were made jointly by Paula Litkey and me. Juha Hyyppä was the advisor in the study. Harri Kaartinen, Antero Kukko and I made the field surveys. Harri Kaartinen provided the reference data. Markus Holopainen was the advisor on forest inventories.

In **III**, I developed the concept and method, carried out the tests and analyses, and wrote the paper. Juha Hyyppä was the advisor in the study.

In **IV**, I developed the concept and method, carried out the tests and analyses, and wrote the paper. Ville Kankare co-registered the TLS data, extracted point clouds of trees, and provided the field reference data. Xiaowei Yu did the analyses of the stem volume. Juha Hyyppä was the advisor in the study. Markus Holopainen was the advisor on forest inventories.

In **V**, I developed the concept, processed the data to produce the stem models, and participated in the paper writing. Xiaowei Yu was the author responsible for writing the paper. Juha Hyyppä was the advisor in the study. Ville Kankare co-registered the TLS data, extracted point clouds of trees, and provided the field reference data. Mikko Vastaranta, Ville Kankare, and I participated in field measurements. Markus Holopainen was the advisor on forest inventories.

In **VI**, I developed the concept and method, carried out the tests and analyses, and wrote the paper. Juha Hyyppä was the advisor in the study. Harri Kaartinen made the field surveys and co-registered the bi-temporal data. Markus Holopainen was the advisor on forest inventories. Timo Melkas provided the reference data.

All co-authors commented the paper.

LIST OF ABBREVIATIONS

ALS	Airborne Laser Scanning
GPS	Global Positioning System
DBH	Diameter at Breast Height
LAI	Leaf Area Index
LiDAR	Light Detection And Ranging
MLS	Mobile Laser Scanning
MSS	Multi-Single-Scan
RS	Remote Sensing
TLS	Terrestrial Laser Scanning
2-D	two-dimensional
3-D	three-dimensional

1. INTRODUCTION

1.1 Background and motivation of the study

Managed forests are the primary source of wood that is a renewable resource and energy. Efficient, optimized forest management is essential for a sustainable wood supply, and such management depends on detailed and up-to-date knowledge of forest resources.

The retrieval of stand information for large areas has been conducted primarily using remote sensing (RS) techniques since RS data became available for practical operations. The accuracy of such information retrieval is highly dependent on the quality and quantity of the field reference data collected on sample plots. The field reference data are used as a reference for the calibration of large-area measurements and also play a central role in the development and updating of regional and national allometric models for estimating important tree attributes that are not directly measurable.

Reference data for sample plots are conventionally collected through manual measurements, which are typically expensive and labor-intensive (Pouliot et al., 2002; Holmstrom et al., 2003). The attributes that are measured in operational field inventories are limited to those measurable with reasonable cost and accuracy using simple tools, such as calipers and measuring tape. The diameter at breast height (DBH) is the most frequently measured and utilized tree parameter and is considered to be the most important parameter in forestry decision-making. Other tree attributes such as the location, tree height and height of the first living branch may also be recorded but are often not measured for every tree on sample plots because they are labor-intensive. Many other important tree attributes, such as the stem curve, are not practically measurable using simple tools. Automated and cost-effective techniques are needed to provide plotwise field inventory data.

Terrestrial laser scanning (TLS), also known as ground-based LiDAR, has been recently shown to be a promising technique for forest field inventories at the plot level (Erikson and Karin, 2003; Simonse et al., 2003; Watt et al., 2003; Aschoff and Spiecker, 2004; Haala et al., 2004; Hopkinson et al., 2004; Thies and Spiecker, 2004). TLS automatically measures the surrounding three-dimensional (3-D) space by tens of millions of non-specific 3-D points within a short period of time. The major advantage of using TLS in forest field inventories lies in its capacity to document the forest in detail. In the application of sophisticated processing methods, TLS can provide both accurate and cost-effective stand attributes for forestry applications. TLS data also permit time series analyses because the entire plot can be documented consecutively over time.

Many tree attributes have been shown to be measurable using TLS data in the laboratory or for individual trees in research studies, but TLS has not been used in operational plotwise forest inventories. The application of TLS data in forest inventories is currently hampered by the relatively high cost of the TLS instrument, the low measurement accuracy achieved using the automated data processing currently available (especially in dense forests with poor visibility), the shortage of experimental results related to the retrieval of advanced stem attributes and to different forest conditions, and the lack of expertise and personnel training. The fundamental challenge is the lack of automated point cloud processing techniques.

1.2 Hypotheses

The following hypotheses were evaluated in this study:

- TLS is capable of documenting a forest sample plot in detail.
- Sample plots can be mapped in an automated and non-invasive manner in boreal forests using TLS data.

- Automated mapping methods can be developed for mapping sample plots at a reasonable cost and with acceptable accuracy.
- The automated mapping methods can provide accurate tree attributes that are measurable or not measurable using conventional field measurement tools.
- These automated mapping methods can be utilized in plotwise forest inventories.

1.3 Objectives of the study

The main objective of the study was to demonstrate the feasibility of TLS in plotwise forest assessment. The sub-objectives were as follows:

- to develop automated methods to detect individual trees from point cloud data.
- to develop automated methods to retrieve basic tree attributes, such as tree location and DBH, that are commonly utilized in forest inventories.
- to develop a new measurement concept for the application of TLS in plotwise forest inventories, i.e., a multi-single-scan (MSS) approach.
- to demonstrate the capability of TLS to accurately and non-invasively collect the stem curve, which is not possible using conventional measurement tools.
- to demonstrate the capability of TLS to accurately and automatically collect stem volume and biomass information.
- to demonstrate the potential application of TLS in bi-temporal forest inventories.
- to show that TLS is an applicable technique in plotwise forest inventories.

1.4 Structure of the study

The study consists of a summary and six original publications. Following this introductory section, Section 2 presents a literature review of conventional field measurement methods used in sample plots, principles of TLS, and studies that have applied TLS in plotwise forest inventories and related forest research. Section 3 describes the materials and basic methods used in the studies. Section 4 summarizes the results of the study, including the methods developed for plotwise sample plot mapping and the test results obtained using the methods. Section 5 discussed the applicability of the results of this study for practical mapping applications and for further research. Section 6 presents the summary and conclusions of this study.

1.5 Contributions of the study

The contributions of the original publications can be summarized as follows:

- Paper **I** discussed the mapping of tree stem locations using the single-scan TLS data. A new type of method was proposed. To the best of the author’s knowledge, this is the first study to use this type of method, i.e., a 3-D point processing technique, in plotwise forest inventories, and this is the only detailed study to date on the application of single-scan TLS data in high-density forest plots.
- Paper **II** discussed the same topic as paper **I** did, using the type of method reported in previous references, i.e., a two-dimensional (2-D) data processing technique. A new processing method that uses a cylinder coordinate system was proposed. The

experimental results showed that a stem far from the scanning location can be detected using the proposed method. To the best of the author's knowledge, this is the first detailed study of detection accuracy as a function of distance using single-scan TLS data in a large sample plot.

- Paper **III** developed a new measurement concept, i.e., MSS approach, for the application of TLS in plotwise forest inventories. The MSS approach significantly improves the mapping results in comparison with those obtained using the single-scan approach. The MSS approach achieves results similar to those obtained using multi-scan methods as reported in previous references in which artificial reference targets and point-level registration were required. The non-reference-target matching leads to time savings in forest plot measurements. This concept can be utilized in many applications, including the automated registration of several scans at the point level.
- Paper **IV** discussed and demonstrated the feasibility of automated, non-invasive measurement of the stem curve and volume. This is the first detailed study of the measurement of stem curve and volume using TLS. The experimental results showed that fully automated stem curve measurement from the point cloud yielded an accurate result. Manual measurement using the same point cloud data had similar accuracy, but the diameters measured at the upper part of the stems were clearly less than with automated processing.
- Paper **V** described the automated, non-invasive measurement of stem biomass. This is the first detailed study of automated stem biomass measurement using TLS for plotwise forest inventories. The experimental results showed that stem biomass, including both stem wood and bark, was estimated with a high degree of accuracy.
- Paper **VI** presented an automated algorithm using bi-temporal TLS data to detect forest structure changes in a typical boreal forest environment. To the best of the author's knowledge, this is the first detailed study of the detection of forest structure changes on sample plots using bi-temporal TLS data. This study demonstrates that bi-temporal, terrestrially collected laser point clouds provide an alternative to traditional manual field investigation in the collection of data on forest structure changes. The algorithm developed in this paper can also be utilized to detect changes of other tree attributes, such as volume and biomass, when used together with the algorithms proposed in papers **IV** and **V**.

2. LITERATURE REVIEW

2.1 Conventional field reference data collection on sample plots in forest inventories

A permanent sample plot in national forest inventories is typically a small area of the forest with a radius of approximately 10 m. The tree information is collected on sample plots to provide field reference data for large-area inventories, which have been conducted primarily using RS techniques since RS data were available for operational inventories. The accuracy of the information retrieval for large areas is highly dependent on the quality and quantity of the field reference data. The field reference data also provide the essential basis for the development and updating of regional and national allometric models for estimating tree attributes that are not directly measurable, such as volume and biomass.

Tree attributes in conventional plotwise forest inventories are measured using both destructive and non-destructive methods. Destructive measurements are typically accurate. However, they require a high amount of resources and are therefore extremely expensive. In addition, destructive measurements are not applicable or acceptable in many cases, e.g., in urban forests and parks and in conservation areas. Therefore, destructive measurements are used only occasionally, e.g., for the estimation of stem volume in pre-harvest inventories using logging machines.

Non-destructive measurements are typically made to collect tree attributes on sample plots. Various instruments have been developed and used for measuring trees in the field. For example, tree diameters can be measured using calipers, diameter tapes or optical devices, and tree heights can be measured using level rods, poles or hypsometers. These tools are low-cost and relatively reliable. However, the uncertainty of the measurement depends on the visibility of the stem, and the tree attributes that can be collected are limited to those that are measurable with a reasonable cost and accuracy, such as tree height and DBH.

Certain important tree attributes are not practically measurable using non-destructive methods. For these attributes, allometric models have been developed and utilized. For example, the tree height is not usually measured from every tree in a sample plot; only sample trees are measured and heights of the all trees are achieved by local model, $h = f(DBH)$. The tree stem curve, which is the key input in the estimation of stem volume, is another example. Allometric models model stem tapering using tree height, species, and DBH as predictors. The applicability of allometric functions is limited to particular climatic, geographic and silvicultural conditions because they are developed using local or national sample data. Studies have shown that the application of inappropriate models can lead to large errors. For example, it was reported that volume estimation errors were as high as 30% at a tree level (Wiant et al., 2002).

There have been many attempts to measure trees on sample plots. For example, the roots of research on stem curve functions date back to the 19^{th} century (Gaffrey et al., 1998). Functions with various forms and complexities have been proposed, and the associated research is ongoing (Rojo et al., 2005; Lappi, 2006; Yang et al., 2009; Li and Weiskittel, 2010; Fonweban et al., 2011). The shortage of accurate and direct measurement methods has been a major factor hampering the advancement of field inventory techniques. More automated and more cost-effective techniques are needed. The TLS technique has the potential to substantially improve the efficiency, accuracy, and capability of knowledge acquisition using plotwise data.

2.2 Principles of TLS

Terrestrial laser scanning (TLS), also known as ground-based LiDAR, uses a laser and a scanning system to automatically measure the surrounding environment during a very short time-frame. The TLS is typically mounted on a tripod over a ground position specified by a certain application. The objects around the static scanning position are captured by 3-D points reflected by the nearest object surfaces in the direction of the laser beams.

Laser measurements have been utilized in standard surveying instruments for the past three decades, such as the laser rangefinders, profilers, and levels. The total station, for instance, utilizes laser rangefinders and angular encoders to measure individual feature points with a high degree of accuracy by a field surveyor. This measuring mechanism, which is manual and specific, was further developed into the concept of the automated documentation of the entire surrounding 3-D space by tens of millions of non-specific 3-D points, i.e., terrestrial laser scanning.

The data collected by TLS comprise a large, dense point cloud, which is a set of 3-D coordinates in a common reference system. Based on these spatial properties (e.g., 3-D coordinates), the point cloud may also include additional features, such as intensity, spectrum values, and waveform. The waveform consists of consecutive digitized samples of a backscattered laser signal at the receiver, which records the object positions and the relationships between objects within a laser footprint. Different TLS instruments may work according to different measuring principles and, therefore, provide different data sets. However, all TLS instruments provide data in the form of 3-D coordinates.

The capability of TLS to capture tens of millions of measurements of the surrounding environment is based on scanning mechanisms. An example is shown in Figure 1. In a typical commercial TLS, the scanner measures the surrounding environment in horizontal and vertical directions stepwise, with a fast vertical mirror rotation and a slower horizontal instrument rotation. In the vertical direction, the laser beam starts, for example, from the scanner zenith and rotates to the lowest scanning position below the horizontal plane of the instrument, and the laser beam then continues to the scanner zenith on the other side of the instrument. In the horizontal direction, the scanner turns 180° and scans both sides of the instrument simultaneously. Details on the scanning mechanism, measuring technique, and pattern and coverage of TLS scanners are presented by (Petrie and Toth, 2009; Reshetyuk, 2009).

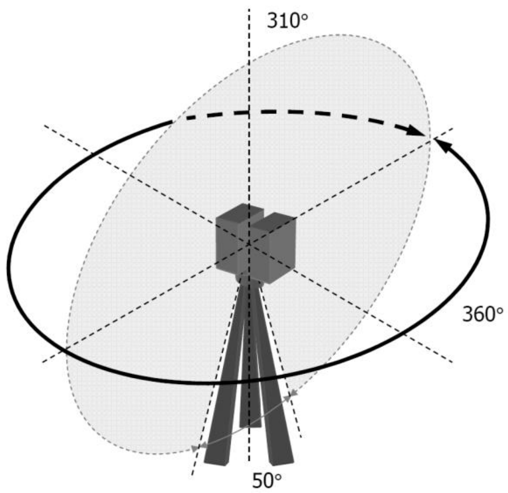


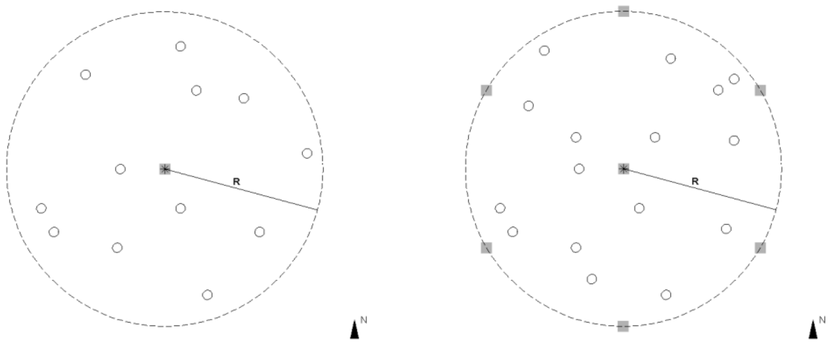
Figure 1. The scanning mechanism of the TLS scanner.

At each measuring position, the range between the instrument and the object is recorded by a laser rangefinder, and the two associated angles are recorded by angular encoders.

These measurements are in an instrument-centered polar coordinate system. They are later transformed to an instrument-centered Cartesian coordinate system, i.e., the point cloud. The point cloud has the capability to document forest horizontal and vertical structures in detail.

2.3 TLS measurements on sample plots

TLS measurements on sample plots are typically made using either a single-scan or multi-scan approach, as shown in Figure 2. In the single-scan approach, the laser scanner is placed at the center of the plot, creating only one full field-of-view (e.g., 360 degrees by 310 degrees) scan, and all trees are mapped from the single-scan point cloud. In the multi-scan approach, several scans are made simultaneously inside and outside of the plot to collect point clouds representing all trees within the plot, and these scans are accurately co-registered by using artificial reference targets that are manually placed throughout the plot.



(a) (b)

Figure 2. The scanning scenario of single-scan (a) and multi-scan (b) approaches. The sample plot is a circular area with radius R. The plot center is marked by an asterisk, and the positions of the trees are shown as solid circles. The gray squares indicate the scanning locations.

The major problem with the single-scan approach is the low detection rate. In single-scan data, the objects behind the nearest surfaces in the direction of the laser beams are missed. The occlusion effect increases as the range of the scanner increases, depending on the attributes of the forest. Studies have shown that up to 32% of all trees in the sample plot are not scanned from the plot center by utilizing single-scan approach because they are occluded by other trees closer to the scanning position (Brolly and Kiraly, 2009; Murphy et al., 2010; Lovell et al., 2011). This occlusion effect increases with increasing distance from the scanner.

The multi-scan approach appears to be the most accurate technique for mapping sample plots. It has the potential to cover almost 100% of the trees and to provide full coverage of the stem surface as a tree is scanned from several directions. However, the multi-scan approach is not always practical because of the cost of the manual or semi-automated processing in the registration of several scans. The registration of several scans on sample plots is currently accomplished by applying artificial objects as the reference targets, and the co-registration is performed manually or semi-automatically using these targets. The difficulty of using artificial targets lies in the requirement for additional effort and knowledge. The field crews need to carry reference targets and tripods, which are typically quite heavy, throughout the field measurements. The crews also need to have experience in using reference targets properly (e.g., to ensure that the targets have good network geometry).

New measurement techniques and processing methods need to be developed to solve the problems of the single- and multi-scan approaches.

2.4 Studies of the application of TLS in plotwise forest inventories

Three fundamental aspects shape the application of TLS in plotwise forest inventories. First, the cost of the field data collection and the associated data processing should be affordable. Plotwise forest inventories are operational work. The methods and algorithms must be economically feasible. Second, the application of TLS in plotwise forest inventories is focused primarily on those tree attributes that are important for forest management and decision-making. Eventually, all tree attributes are useful for management activities. However, only some of them (e.g., wood volume) are important for forestry. Many tree/stand attributes (e.g., the leaf area index; LAI) are not directly utilized in management activities. Third, the accuracy of the estimation of tree attributes should be acceptable. Forest management requires accurate and up-to-date information. Estimation accuracy is a key output of the application of TLS in plotwise forest inventories.

TLS attracted interest as a technique for obtaining plotwise forest field inventory data in the early 2000s, and the first reports based on this technique were published in 2003 (Erikson and Karin, 2003; Simonse et al., 2003; Watt et al., 2003) and 2004 (Aschoff and Spiecker, 2004; Haala et al., 2004; Hopkinson et al., 2004; Thies and Spiecker, 2004). The objective of these early studies was to discuss the possible applications of TLS to field inventories, such as the possibility of finding trees and measuring DBH and tree height. Automated solutions and the applicability of TLS in different types of forest were not considered.

A variety of methods were proposed and tested in subsequent years. The results reported varied for different types of forests and different scanning scenarios, indicating that the methods are still under development. For example, the root mean squared error (RMSE) of DBH estimation was 1.80 cm using a single-scan approach (Maas et al., 2008) and 3.74 cm using a multi-scan approach (Huang et al., 2011) on sparse plots (212 stems/ha). The single-scan approach is presumed to be a less optimal data source than the multi-scan approach. Proposals were made at this stage to improve the performance of certain methods, i.e., pre-scan preparations, such as the removal of lower tree branches or the clearance of undergrowth. The greater was the number of pre-scan preparations, the better were the results of tree attribute extraction (Murphy et al., 2010). However, such preparation is neither desirable in field measurements nor acceptable in many applications, because it requires additional field work and damages trees. The utilization of this concept in field data collection clearly shows that fully-automated processing is very challenging. Major studies were, however, conducted on sample plots scanned as they are (Erikson and Karin, 2003; Simonse et al., 2003; Watt et al., 2003; Aschoff and Spiecker, 2004; Haala et al., 2004; Thies and Spiecker, 2004; Hopkinson et al., 2004; Watt and Donoghue, 2005; Liang et al., 2008; Litkey et al., 2008; Maas et al., 2008; Brolly and Kiraly, 2009; Tansey et al., 2009; Huang et al., 2011; Lovell et al., 2011). These numerous studies show that fully-automated methods should be developed and are being developed.

The initial motivation for using TLS in plotwise forest inventories was to replace manually measured tree attributes with those retrieved automatically from TLS data. This concept has been widely accepted and is still influential because foresters require new techniques to improve their work efficiency and because new techniques are supposed to be at least as good as the old ones. Studies have therefore been focused primarily on the extraction of the tree attributes that are most commonly used in forest decision-making, i.e., position and DBH (Simonse et al., 2003; Aschoff and Spiecker, 2004; Thies and Spiecker, 2004; Hopkinson et al., 2004; Watt and Donoghue, 2005; Wezyk et al., 2007;

Liang et al., 2008; Litkey et al., 2008; Maas et al., 2008; Brolly and Kiraly, 2009; Tansey et al., 2009; Huang et al., 2011; Lovell et al., 2011). The most popular method for locating trees and determining DBH is to cut a slice of data from the original point cloud and to identify and model tree stems in this layer by point clustering or circle finding (Simonse et al., 2003; Aschoff and Spiecker, 2004; Thies and Spiecker, 2004; Watt and Donoghue, 2005; Maas et al., 2008; Brolly and Kiraly, 2009; Tansey et al., 2009; Huang et al., 2011). The problem with this idea is its assumption that all trees present a clear stem at the same height at which the slice goes through the point cloud. This assumption is not valid in most mixed forests because trees have branches at different heights, and nearby branches may be overlapped in the layer. A study of a mixed deciduous stand showed difficulties in manual stem detection in a TLS data layer (Hopkinson et al., 2004). Results from studies of different types of forests were highly variable, indicating the need for more research on these topics.

Studies were also made on the measurement of tree attributes from TLS data that are not measurable using conventional tools, e.g., two studies of the measurement of stem curves of individual trees (Henning and Radtke, 2006; Maas et al., 2008). Further research is needed to explore the applicability of measuring advanced tree attributes on a plot level.

There has been increasing interest recently in studies using the single-scan approach (Liang et al., 2008; Litkey et al., 2008; Maas et al., 2008; Strahler et al., 2008; Brolly and Kiraly, 2009; Lovell et al., 2011), although the multi-scan approach is considered to be the best method in regard to the estimation of tree attributes. The main reason for interest in the single-scan approach is most likely that it is easy to implement and does not require registrations of point clouds of several scans.

In conventional plotwise field inventories, either mean values or the attributes of all trees are recorded. Multi-scan data are therefore considered to be the best data source because they record all trees on the sample plot. However, the multi-scan approach costs a lot for data collection and processing. In contrast, the single-scan approach does not require any data registration, and the cost of data collection and pre-processing is much less than for the multi-scan approach. The main drawback of the single-scan approach is its low stem-detection accuracy, which is approximaetly 40-82% (Strahler et al., 2008; Murphy et al., 2010; Brolly and Kiraly, 2009; Lovell et al., 2011). However, it is possible to use the trees available in the single-scan data rather than all of the trees on the sample plot. If this idea can be successfully applied, the expenses of the field inventory will be reduced. This potential new research direction could have great practical impacts but has not been discussed in detail to date.

After a decade of study, TLS has not yet been accepted as an operational tool in plotwise forest inventories. Its application is hampered mainly by difficulties in the automation of the point cloud processing that provides convincing measurement results of the most important forest inventory parameters.

2.5 Studies of the application of TLS in tree-related topics

The discussion in this study regards the feasibility of applying TLS in plotwise forest inventories. The focus of this study is on developing algorithms and methods of retrieving tree attributes that are important and widely utilized in forest managements and decision-making. TLS has been applied in several tree-related research areas, including forest ecology and individual tree structure. Forest inventory studies and tree-related research are sometimes confused because they both involve standing trees. This section briefly outlines other types of tree-related research and their differences from forest inventory research. The utilization of TLS in these other types of tree-related research is outside the scope of this study and is not further discussed.

The application of TLS in ecological studies

The forest is an important ecosystem that includes a large number of plants, animals, and microorganisms. The forest ecosystem has complex interactions with other ecosystems and greatly impacts human society. Trees, a major component of the forest ecosystem, receive close attention because of their economic and environmental roles. TLS data have been utilized in forest ecological studies since the TLS instrument first became available (Lovell et al., 2003; Hosoi and Omasa, 2006; Danson et al., 2007; Strahler et al., 2008).

Forest ecological research and plotwise inventories share certain common interests, such as the collection of basic tree attributes, including tree species, height, and DBH. However, most of the tree attributes that are intensively studied in forest ecology, such as leaf area density (Hosoi and Omasa, 2006), leaf area index (Jupp et al., 2009; Antonarakis et al., 2010; Huang and Pretzsch, 2010), canopy gap (Danson et al., 2007), and leaf orientation (Hosoi and Omasa, 2006), are not covered by forest inventory studies.

Nevertheless, studies in these two disciplines are valuable references for each other. For example, methods for the estimation of basic tree attributes can be used in both areas. Studies in the two disciplines are not directly comparable currently because they are conducted using different methodologies. Results are often evaluated on the basis of correlations in ecological studies, whereas they are evaluated on the basis of measurement bias and errors in plotwise inventories. It would be beneficial to report measurement errors in both disciplines in the future.

The estimation of tree attributes on the individual tree level

Realistic tree modeling is an important topic in computer graphics. The data used have consisted primarily of photographs (Shlyakhter et al., 2001; Neubert et al., 2007). TLS provides another data source for tree modeling and has received close attention (Cheng et al., 2007; Xu et al., 2007). The modeling of individual trees has been studied in the RS area ever since TLS became available (Gorte and Pfeifer, 2004; Pfeifer et al., 2004; Pfeifer and Winterhalder, 2004; Thies et al., 2004), and this type of research has gained great popularity in recent years (Bucksch and Lindenbergh, 2008; Côté et al., 2009; Bucksch and Fleck, 2011; Côté et al., 2011; Moorthy et al., 2011; Dassot et al., 2012).

Individual-tree studies assume that trees are completely or mostly standing by themselves and are captured by point clouds. These hypotheses have been confirmed in certain cases, such as street trees (Lefsky and McHale, 2008) and laboratory studies (Keightley and Bawden, 2010; Seidel et al., 2011). Individual trees can be also found in the field, e.g., individual trees standing alone (Côté et al., 2009, 2011; Dassot et al., 2012; Moorthy et al., 2011), trees manually separated from the point cloud (Fleck et al., 2011), or trees on sparse sample plots (Maas et al., 2008).

TLS data used in individual-tree studies are collected using the best possible conditions, to avoid occlusion and to obtain optimal point cloud data. In (Dassot et al., 2012), for example, each individual tree was scanned from three or four positions around it, and the scans were co-registered using five reference spheres. The cost of the data collection is not a major concern in these studies, which would definitely be too high if such a scanning scenario were used in operational projects.

Various methods have been described for the measurement of individual trees using TLS data, such as stem curve (Henning and Radtke, 2006), volume (Lefsky and McHale, 2008; Keightley and Bawden, 2010; Dassot et al., 2012), crown projection area (Puttonen et al., 2010; Fleck et al., 2011), and biomass (Holopainen et al., 2011; Seidel et al., 2011).

Different hypotheses lead to different methodologies in individual-tree and plotwise studies. The techniques developed for plotwise studies are sometimes redundant when only one tree is considered. For example, the occlusion effects in single-scan TLS data may introduce great difficulties in the estimation of plotwise tree attributes, but they are seldom considered as a challenge in individual-tree studies because the trees are mostly covered by point clouds. There has been no report to date indicating that the methods developed for individual-tree studies are directly applicable to plotwise studies. The methods developed for different purposes should be evaluated on different bases in the future.

Individual-tree studies explore the possibility of applying TLS in the estimation of tree attributes on fine scales. These studies may also improve our understanding of how TLS can be applied in plotwise forest inventories and indicate what types of results can be expected if the hypotheses addressed in individual-tree studies are confirmed. However, currently and in the near future, those hypotheses cannot be confirmed in plotwise forest inventories because of the cost concern.

3. MATERIALS AND METHODS

3.1 Study areas and materials

Study areas in **I** and **III-VI** were located in Evo, southern Finland (61.19° N, 25.11° E). The area is part of the southern Boreal Forest Zone and comprises approximately 2000 ha of primarily managed boreal forest. Plotwise tree-by-tree field measurements were performed from 2007 to 2009. Some destructive measurements were performed in 2010 in the field and in laboratories.

Study area in **II** was located in Kajaani, eastern Finland (64.14° N, 27.44° E). The area comprises primarily managed boreal forest. The field measurements were performed at the plot level. References of individual trees (e.g., tree locations) were not available. Tree-level measurements were performed manually in the point cloud.

The locations of the study areas are shown in Figure 3. The selection of these study areas was based on availability. Further details of the datasets are presented in papers **I**-**VI**.

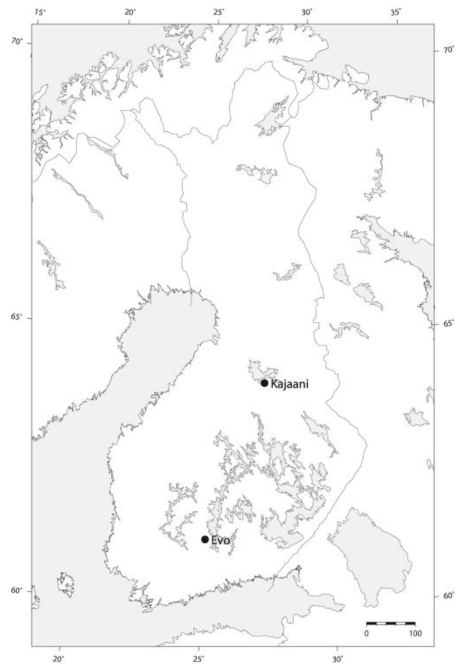


Figure 3. The locations of the study areas.

The tree-level forest inventory data were collected manually using conventional field measurement tools. The coordinates of the plot centers were measured using a Trimble GEOXM 2005 GPS device and were post-processed using local base station data. The angles of the trees were determined using a Suunto bearing compass (Suunto Oy, Vantaa, Finland), and the distance from the plot center was measured using a Haglöf Vertex laser rangefinder (Haglöf Sweden AB, Långsele, Sweden). The locations of the trees were calculated using these angle, distance, and plot center data. The absolute spatial accuracies of the stem location measurements varied depending on the plot attributes. The relative accuracy was assumed to be good because each stem location was referenced to the same point, i.e., the plot center. The DBH was measured to the nearest millimeter using steel calipers. The heights of the tree and the first living branch were measured using a Haglöf Vertex laser rangefinder.

Destructive measurements were performed to obtain stem curves and biomass data, which were utilized in papers **IV** and **V**.

The trees were felled, and all branches were trimmed away. The tree stems were cut into logs. The first cut was made at the stump height. The second cut was made at a point halfway between the stump height and breast height (1.3 m), and the third cut was made at breast height. Starting at 2 m, the cuts were made at every meter to the top of the stem. The stem diameter was measured at the base of each log to the nearest millimeter using steel calipers. These measurements provided the stem curves of the trees.

The fresh weight of the logs was measured using a scale. A sample disc of 15 cm height was cut from every other log and was divided into stem wood and bark. The discs were dried in an oven at 70 °C for 2-3 days in the laboratory, and their dry weights were measured. The ratio between the fresh and dry weights was calculated. The bark and the wood were measured separately because their moisture content was most likely different. The proportion of bark was estimated using the dry weights of wood and bark. The dry weight, or the biomass, of all logs was then calculated using the fresh weight of logs and the ratio value. One ratio value was used in the calculation of the adjacent log and the log to which it belonged.

In the Kajaani study area, there were no tree-level reference data. Manual measurements from the point cloud were utilized to obtain the reference. The location of the tree stem was determined visually and measured from the intensity image of the point cloud and was verified using a 3-D view of the measured points. These measurements made it possible to study the stem mapping accuracy at a distance because it was not practical to measure all trees on a plot having a radius of several dozen meters. This reference contributed to the study of TLS application in forest inventories.

Studies of TLS in forest inventories have been focused primarily on the permanent plots used in national forest inventories, which are typically small areas with a radius of approximately 10 m. The size of permanent plots is small because it is very demanding and generally impractical for forest inventories to collect reference data on circular plots with radii larger than 10-12 m using conventional measurement methods, particularly if the stem count per hectare is high. Many commercial TLS scanners have a measurement range of approximately 70 m. It is of interest to determine the performance of stem mapping at the middle and far range of the scanner’s measurement range. The manual stem location mapping in the point cloud makes it possible to measure trees at a distance (up to 70 meters from the scanner in this case) and to evaluate the accuracy of stem mapping at a distance.

TLS data were collected from the sample plots from 2007 to 2010. Different scanning set-ups were utilized depending on the study topic. In **I** and **II**, the stem location mapping was studied. The sample plots were scanned using a single-scan approach. The scanner was placed at the scan center and a full field of view scan was performed. In **VI**, the applicability of bi-temporal TLS data for forest structure change mapping was discussed. Two scanning campaigns were conducted before and after a thinning operation using a single-scan approach. On each sample plot, the center point was marked on the ground before the first scan, and the height of the scanner was recorded. In performing the second scan, the scanner was positioned at approximately the same position as in the first scan. In **III**, the MSS approach was proposed for mapping a sample plot. This approach includes the elements from both single-scan and multi-scan approaches. The scans were made at several positions inside and outside the sample plots without using reference targets. In **IV** and **V**, the measurement of the stem curve and the estimation of the stem volume and biomass were quantitatively studied. The multi-scan approach was utilized to minimize the occlusion effect.

Table 1 summarizes the TLS datasets collected in the study.

Table 1. Summary of the TLS datasets collected.

Paper	Area	Plots	Acquisition year	Instrument	Point distance (mm at 10 m)	Scan mode
I	Evo	9	2008	Leica HDS6000	3	single-scan
II	Kajaani	1	2007	Faro LS880HE80	3	single-scan
III	Evo	5	2010	Leica HDS6100	3	multi-single-scan
IV	Evo	9	2010	Leica HDS6100	3	multi-scan
V	Evo	9	2010	Leica HDS6100	3	multi-scan
VI	Evo	5	2008	Leica HDS6000	3	single-scan

Three commercial TLS instruments were used in the data acquisitions: Faro LS880HE80 (FARO USA, Lake Mary, FL, USA) and Leica HDS6000 and HDS6100 (Leica Geosystems AG, Heerbrugg, Switzerland), as summarized in Table 2. All of three scanners used phase-based techniques to measure the range at a high accuracy (e.g., 2-3 mm at 25 m) and to cover the entire surrounding environment with a dual-axis scanning system. The selection of an instrument in the scanning campaigns was based solely on availability. The methods developed in the study are based on the point coordinates alone. All TLS instruments provide such data. The selection of instruments is therefore assumed to have little or no impact on the experiments and the results. In all the scanning campaigns, the scanning resolution was the same and gave a point distance of 3 mm at a distance of 10 m.

Table 2. Specifications of the laser scanners utilized in the field data collection.

Specifications	Faro LS880HE80	Leica HDS6000	Leica HDS6100
Field of view (°)	360×320	360×310	360×310
Measurement range (m)	76	79	79
Distance measurement accuracy (mm)	±3 at 25 m	±2 at 25 m	±2 at 25 m
Data acquisition rate (points per sec)	120 000	500 000	508 000
Max resolution (0.001°)	0.76 × 9	9 × 9	9 × 9
Beam diameter at the exit (mm)	3	3	3
Beam divergence (mrad)	0.25	0.22	0.22
Laser wavelength (nm)	785	650 – 690	650 – 690
Laser power (mW)	20	30	30
Weight (kg)	14.5	14	14
Dimensions (L×W×H, mm)	400×160× 280	199×294×360	199×294×360
Operating temperature (°C)	5 – 40	0 – 45	-10 – 45

3.2 Statistical analysis

The quality of the results was evaluated by comparing the results with reference data, which were measured manually using conventional methods.

The accuracy of the detection was evaluated on the basis of omission errors, commission errors, and overall accuracy. Omission errors are objects that are not mapped. Commission errors are objects that are mapped and do not have corresponding reference data. Omission and commission errors were calculated separately for the individual plots. Overall accuracy is the percentage of correct detections and was calculated for all test plots.

The accuracy of the estimations was evaluated using the bias, RMSE, and the relative RMSE, as defined in Equations 1, 2, and 3.

$$Bias = \frac{1}{n}\sum_{i=1}^{n} e_i = \frac{1}{n}\sum_{i=1}^{n}(y_i - y_{ri}) \tag{1}$$

$$RMSE = \sqrt{\frac{\sum(y_i - y_{ri})^2}{n}} \tag{2}$$

$$RMSE\% = \frac{RMSE}{\overline{y_r}} \times 100\% \tag{3}$$

where y_i is the i^{th} estimation, y_{ri} is the i^{th} reference, $\overline{y_r}$ is the mean of the reference values, and n is the number of estimations.

4. RESULTS

Basic tree attributes (e.g., tree position, height, and DBH) are typically measured using conventional measurement tools in sample plots. The estimation of these basic tree attributes using TLS was studied in **I**–**IV** and **VI**, see section 4.1.

The utilization of TLS data and advanced processing techniques can measure advanced tree attributes, such as stem curves and volume. The feasibility of measuring advanced tree attributes using TLS was studied in **IV** and **V** and reported in section 4.2.

The point cloud data employed in this study were collected using both single-scan and multi-scan approaches. The results achieved using these approaches are discussed in section 4.3. In addition to these two traditional approaches, a new measuring approach was proposed in **III**. This approach leads to more accurate estimations than the single-scan approach and requires less field work than the multi-scan approach. The results of this method are discussed in section 4.4.

The feasibility of measuring plotwise forest structure changes using TLS was studied in **VI**. The results of this method are discussed in section 4.5.

4.1 The estimation of conventional tree attributes

Stem detection

The detection of individual trees in the point cloud is the foundation of tree attribute estimation and is the first topic of this study.

A fully automated algorithm for plotwise stem mapping using single-scan TLS data was developed in **I**. A new type of method was introduced that uses a point-processing technique to detect trees in plotwise forest inventories. This type of method does not require a priori plot knowledge (e.g., digital terrain model) or a specific data format (e.g., image format). Therefore, it can be used in different types of forests and for processing different data sets along the processing pipeline.

The stem points were automatically identified based on the spatial properties of the points. A local coordinate system was established for each point in its neighborhood. In this local coordinate system, the axis directions were defined by eigenvectors, and the variances of the data along the axes were indicated by eigenvalues. A point was on a surface if its neighboring points were distributed primarily along two axes in the local coordinate system. This point was most likely reflected from a tree stem if the direction of the normal vector to the surface was approximately horizontal in the real world coordinate system.

A stem model was reconstructed from the selected points. A tree stem was divided into a series of small sections along the stem profile. In each section, a 3-D cylinder was fit to the point cloud. Figure 4 illustrates a cylinder and a point on the cylinder surface.

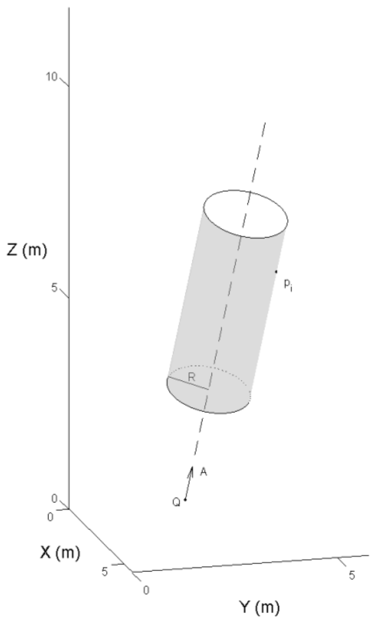


Figure 4. A cylinder and a point on its surface.

The distance, or residual, between the selected laser point and the cylinder surface was minimized to estimate the stem model. To eliminate the outliers from the branches and crowns, a weight was assigned to each point depending on the residual. More details on the robust modeling procedure were given in **I**. Figure 5 illustrates the steps involved in automated stem reconstruction.

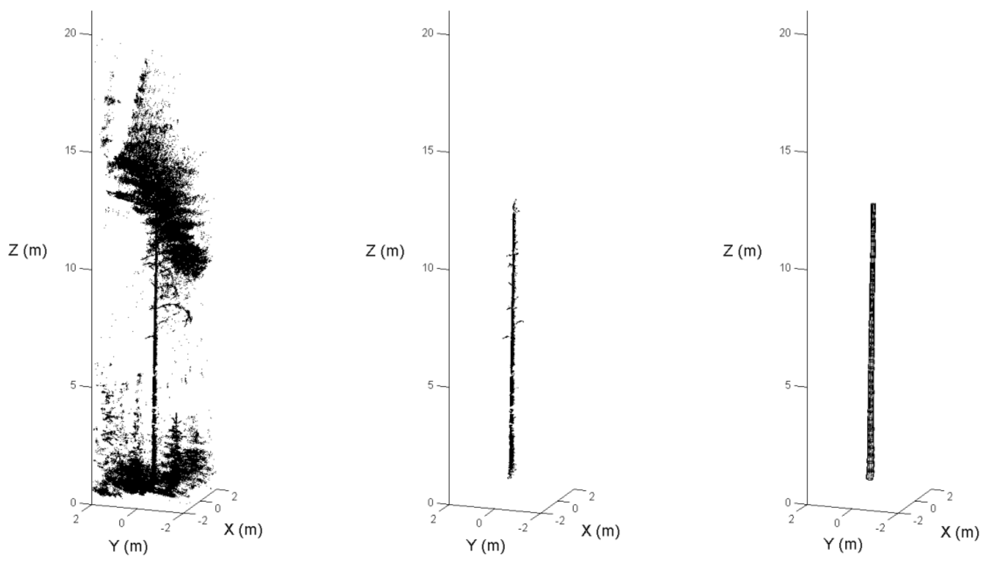


Figure 5. Automated stem reconstruction: (a) the original point cloud of a tree; (b) the detected stem points; and (c) the automatically reconstructed stem model.

The stem-detection method has been tested on different kinds (density, species and development class) of forests in **I** and **III**–**VI** and on both single-scan and multi-scan data sets. Stem detection in dense sample plots using single-scan data was studied in **I** and **III**. In **I**, the overall detection accuracy was 73% for nine sample plots (the average stem density was 1022 stems/ha). In **III**, the overall detection accuracy was 73.4% for five sample plots (the average stem density was 815 stems/ha), which is close to the result in **I**.

The stem-detection method proposed in **I** is a two-step procedure, i.e., stem point recognition and stem modeling, which are closely integrated but independent processes. Therefore, the method provides an extendable framework. New techniques can be easily integrated into this procedure. For instance, the stem points are currently located using a 3-D point processing method. Waveform or multi-spectrum TLS data could be used to detect stem points in the future when such data are more commonly available.

Another automated algorithm for plotwise stem mapping using single-scan TLS data was developed in **II**. This method is based on range-image structure. This range image is not always available or not always convenient to be reconstructed. It may be deleted before data delivery or destroyed at some stage to reduce data volume. However, the utilization of range-image structure in data processing has certain advantages. The 3-D spatial distribution of the points in the object space is implicitly expressed by the 2-D spatial distribution of pixels in the range image. The point clustering in local 2-D image space using spatial features functions similarly to that in local 3-D space using XYZ coordinates. A new method, scan line continuousness segmentation, was developed and the cylinder coordinate system was first used in **II**. The approach is based on the continuity property of the object surface, planar distance and segmentation in the horizontal and vertical directions. The experimental result indicates that trees that are far from the scanning location can be detected. The detection accuracy for the trees captured by the point cloud data was 85% for trees up to 60 m away.

DBH measurement

DBH measurement at the plot level was studied in **III** and **VI**.

The diameter of the cylinder element at breast height was utilized as the estimate of the tree’s DBH. Breast height was defined as a point 1.3 m above ground level, and the ground height was estimated based on the lowest data point around the stem model. This estimate may lead to some measurement errors, as breast height should be located 1.3 m above the base of the tree.

DBH was estimated using single-scan and MSS approaches in **III**. The RMSE of the DBH estimation using the MSS method ranged from 0.90 cm to 1.90 cm, and the mean bias was 0.47 cm. The RMSE of the DBH estimation using the single-scan method ranged from 0.74 cm to 2.41 cm, and the mean bias was 0.35 cm. All of these results were at the plot level.

The DBH at the tree level was estimated using single-scan data in **VI**. The RMSE of the DBH estimation was 1.29 cm and the bias was 0.16 cm for changed trees.

Tree height measurement

Tree height measurement was studied in **III** using single-scan and MSS approaches.

Tree height was calculated as the difference in height between the highest laser point around the stem model and the ground level (defined as above).

The five sample plots were densely populated, having an average stem density of 815 stems/ha. The RMSE of the tree height estimates made using the MSS method ranged from 2.04 m to 6.53 m with a mean bias of 1.31 m. The RMSE of the height estimates made using the single-scan method ranged from 1.36 m to 4.29 m, and the mean bias was 0.62

m. All of these results were at the plot level. Tree height was typically overestimated, which is attributed to the stand structure, tree growth, the error in the reference data, and air points in the point cloud.

4.2 The estimation of advanced tree attributes

Stem curve and volume measurement

Stem curves were automatically measured using TLS for different tree species and at different growth stages in **IV**.

Nine plots were scanned as they were, using the multi-scan approach to reduce the occlusion caused by other trees in the plot. Twenty-eight pine and spruce trees were measured destructively to obtain reference stem curve data. These trees were also extracted from the two to three nearest scans to form the point cloud data. The number of nearest scans employed was determined by the visibility of the tree in the point cloud.

The stem models were automatically constructed using the robust modeling method proposed in **I**. The stem curve was estimated using the 3-D model. The model elements were selected at the heights where the reference values had been measured. The total stem volume was computed from the automatically derived stem curve. The stem volume is the sum of the volume of each stem section. For comparison, the stem curves were also manually measured in the point clouds, and the stem volumes were also calculated using nationwide used volume equations (Laasasenaho, 1982), which is based on species, height, DBH, and diameter at 6 m.

The fully automated stem curve measurement using point cloud data yielded an accuracy of approximately 1 cm. Manual measurement from the same data achieved similar accuracy, but the diameters measured at the upper part of the stems were clearly less than with the automated processing. The relatively highest measured heights from the point cloud data were 47.1% for pine trees and 27.8% for spruce trees when using manual measurements versus 65.8% for pine trees and 61.0% for spruce trees when using the automated procedure. These results show that automated processing has the potential to achieve a more accurate stem curve measurement than manual interpretation.

The correlations are high between the calculated and field-measured stem volumes when using automated stem curve measurements and when using the existing volume models. For the automated stem curve measurement, a correlation coefficient of 0.99 and an RMSE of 29.29 dm^3 (9.5%) were achieved. For the stem volume models, Model I (using species, DBH, diameter at 6 m, and tree height as predictors) had a correlation coefficient of 0.99 and an RMSE of 28.92 dm^3 (9.4%), and Model II (using species, DBH, and tree height as predictors) had a correlation coefficient of 0.99 and an RMSE of 32.72 dm^3 (10.6%). These results indicate that the stem volumes obtained using the automated stem curve measurement method and the best Finnish allometric volume model (Laasasenaho, 1982) were equally accurate.

The results of the automated stem curve and volume measurements also show that the estimation accuracy was similar for pine and spruce trees.

Stem biomass estimation

In **V**, stem biomass could be estimated with high accuracy using TLS point clouds and automatically estimated stem curves.

A comparison with destructive biomass measurements indicated that the stem reconstructed from TLS data and corresponding volume of the reconstructed stem correlated highly with stem biomass (R = 0.98). The results indicated that the biomass estimation model performed better than the DBH-based model for predicting stem biomass. Furthermore, the linear form of the estimation model is promising for biomass assessment, as it does not involve the transformation of variables. The use of reconstructed stems in biomass estimation can be applied everywhere, i.e., it could be a general solution to the biomass estimation problem.

4.3 Single-scan and multi-scan measurements

The data employed in **I**–**VI** were captured using single-scan and multi-scan approaches. The results achieved with these two measuring approaches were different.

The DBH of changed stems was automatically measured using single-scan data in **VI**. The RMSE of the estimation was 1.29 cm, and the bias was 0.16 cm at the tree level. In **IV**, the DBH of the trees studied was measured using multi-scan point clouds. The RMSE of the estimation was 0.82 cm and the bias was 0.06 cm. These two results are not directly comparable to each other because they were obtained on different sample plots. However, these results imply that the point clouds captured using multi-scan approaches lead to more accurate parameter estimations.

In theory, the multi-scan approach is the best method for mapping a sample plot with respect to the estimation of tree attributes because trees are fully covered by the merged point cloud. The major problem with the multi-scan method is the point-cloud registration of several scans not yet being fully automated.

4.4 The MSS approach

The MSS approach was proposed in **III** to measure sample plots. This method provides a new method of mapping sample plots without using point-level registration.

The scanning scenario in the MSS approach is similar to that of the multi-scan approach. Several scans are made simultaneously inside and outside of plots. Artificial reference targets are, however, not used in the MSS approach.

The MSS method maps the sample plot in individual scans first and then merges the results to create an overall map of the sample plot, as illustrated in Figure 6. Tree attributes (i.e., stem locations) are extracted from different scans and matched to each other. The information obtained from different scans, e.g., DBH, is combined to support the interpretation of the sample plot.

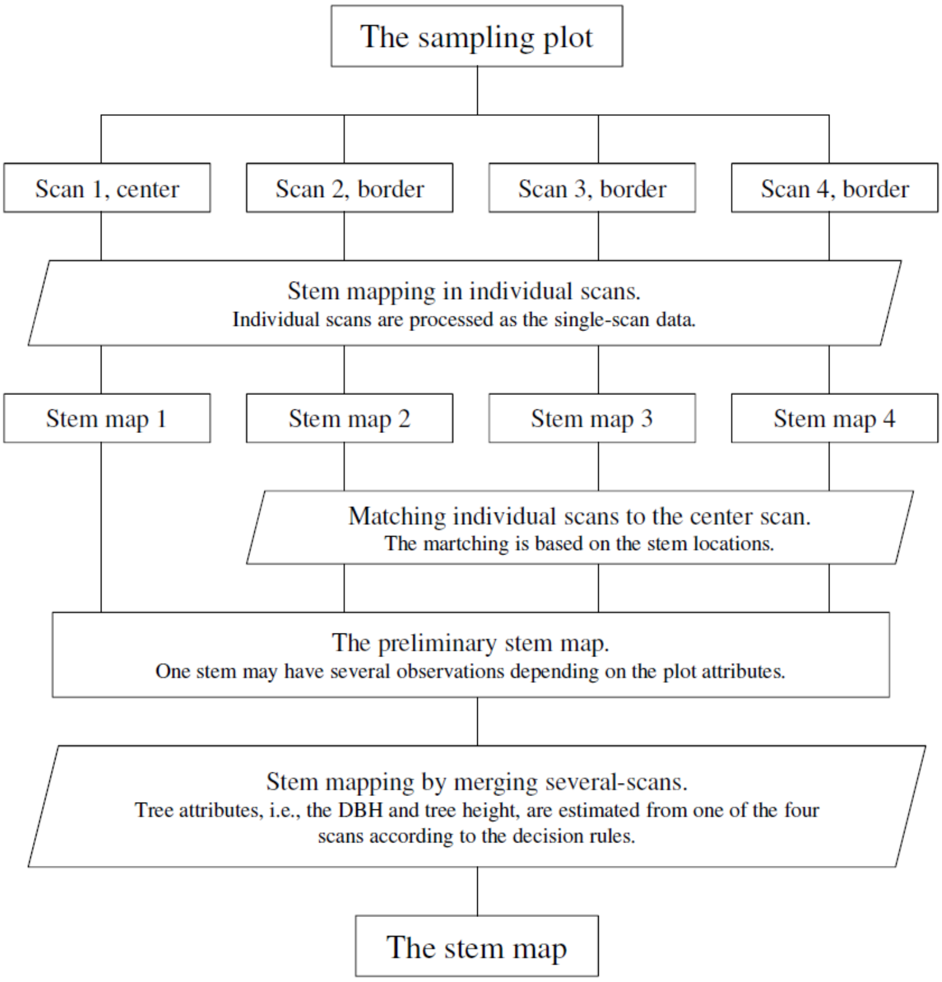


Figure 6. Conceptual diagram of the MSS method.

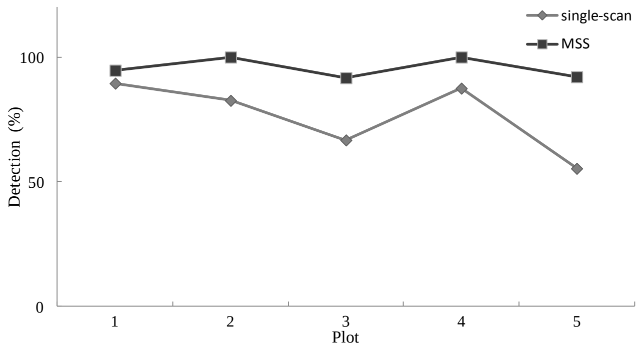
The stem detection accuracy of the MSS method was between 92% and 100% at the plot level. The RMSE of the DBH estimation using the MSS method varied between 0.90 cm and 1.90 cm.

For comparison, the five test plots were also mapped using the single-scan method. The center scan, which was also used in the MSS method, was processed in the same manner as the single-scan data. The single-scan approach measures the sample plot using only one scan (e.g., at the plot center). The major problem with this method is the low detection rate. The MSS method significantly improved the stem-detection accuracy compared with the single-scan approach. The overall stem-detection accuracy using the MSS method was 95.3% compared to 73.4% using the single-scan method with the same data. The improvement is remarkable for plots where the stem density is high (e.g., more than 1000 stems/ha), and it generally decreases as the density decreases.

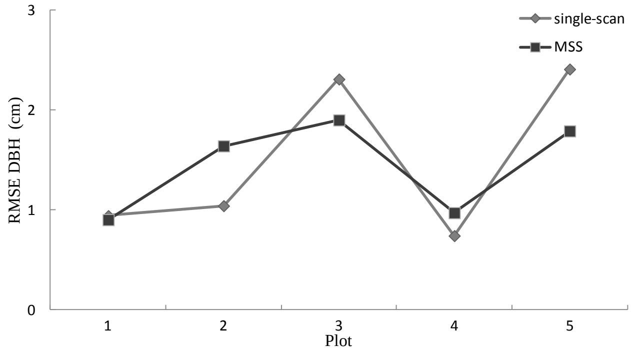
The MSS method also slightly improves the DBH estimation. The RMSE of the DBH estimation using the MSS method ranged from 0.90 cm to 1.90 cm. The RMSE of the DBH estimation using the single-scan method ranged from 0.74 cm to 2.41 cm. In the MSS method, each stem was mapped from the scan in which the stem was closest to the scanning position. This measuring mechanism contributes to a better DBH estimation accuracy.

Tree height was likely overestimated by the MSS method.

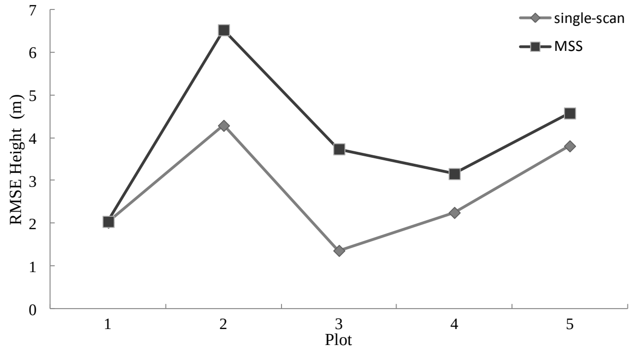
Figure 7 illustrates the mapping results using the MSS and single-scan methods.



(a)



(b)



(c)

Figure 7. The mapping results using the MSS and single-scan methods: (a) the detection rate; (b) the RMSE of the DBH estimation; (c) the RMSE of the tree height estimation.

4.5 Change detection

A fully automated method was proposed in **VI** for the detection of changes in forest structure over time using bi-temporal TLS data.

The algorithm detects changes in the time-series data based on the data and the object basis. In the data-orientated analysis, the approximate changes are detected in the voxel space. Changes are identified by comparing the number of points in voxel units, which is fast and simple. However, the detected changes correspond to various objects on the plot, e.g., the ground and the tree crown. The object-orientated analysis accurately identifies the object subjected to changes by constructing the entire stem model. For example, some stem points may be falsely identified as changed points in the data-orientated analysis because of tree movement caused by the wind. However, it is not possible to construct an entire stem model for such points because the number of points is very limited. In general, object modeling requires far more computation than the comparing operation. The proposed method combines data- and object-oriented analyses. Intensive computation is concentrated on a subset of the original points.

The algorithm was tested in five densely populated managed forest plots using single-scan TLS data. It is worth noting that the method is based on a 3-D point processing technique, and it works for both single- and multi-scan TLS data.

Table 3 summarizes the mapping results. ‘Harvested stems’ refers to the number of harvested stems in the reference data. The mapped changes represent the number of harvested stems detected from the point cloud using the presented method. ‘Omission’ is the number of harvested stems not found. ‘Commission’ is the number of detected harvested stems lacking corresponding references.

Table 3. Summary of change detection from the single-scan TLS data.

Plot	**1**	**2**	**3**	**4**	**5**
Harvested stems	7	10	13	8	12
Mapped stems	7	8	13	5	12
Omission	0	2	0	3	0
Commission	0	0	1	1	0

The overall accuracy of the stem status detection was 96%. The bias of the DBH estimated for the harvested trees was 0.16 cm, and the RMSE was 1.29 cm. If one outlier (that occurred due to heavy occlusion) was removed, the bias was 0.04 cm and the RMSE was 0.98 cm. These results indicate that DBH can be accurately assessed using single-scan data. Therefore, more features of removed trees can be estimated because DBH is widely used as a basic input in tree feature estimation.

The omissions consisted of occluded stems (five in the experiment) for which no adequate point cloud was recorded, and commissions were dead or border trees (two in the experiment) that had not been recorded in the field data. Thus, the developed method identified all of the changed trees that were represented by an adequate point cloud in the time series data.

5. DISCUSSION

5.1 Quality of the results

The results achieved in **I–VI** were evaluated using manual field measurements. In addition, the results are here compared with the results reported in previous studies.

New results were obtained for the following topics:

- The quality and feasibility of applying 2-D and 3-D processing techniques to plotwise stem mapping.
- The quality of stem mapping in high-density sample plots using TLS data.
- The quality and feasibility of merging several single-scans at feature and decision levels for plotwise mapping.
- The quality and feasibility of automatically and non-invasively measuring tree attributes that are important but not measurable using conventional measurement tools.
- The quality and feasibility of applying multi-temporal TLS data to the detection of forest structure changes and to the estimation of the attributes of changed trees.
- The quality of tree attribute estimation using single-scan and multi-scan approaches.
- The feasibility of the automated registration of several point clouds at the point level.
- The feasibility of mapping sample plots of large sizes.

Stem detection

Table 4 summarizes the stem detection accuracy of the single-scan method reported in earlier studies compared with the results in **I** and **III**.

High detection accuracies were reported in early studies only for sparse forests. The detection rate is above 80% in sample plots that have a stem density lower than 410 stems/ha. The detection rate decreases as the stem density increases. The detection accuracy is reported as 59-72% in plots that had a density of up to 735 stems/ha. The instrument used may also influence the result. In (Strahler et al., 2008; Lovell et al., 2011), the detection rates are rather lower in low-density plots. The instrument used in their studies is an experimental full-waveform scanner. The results are most likely related to the measuring mechanism of the scanner.

The overall stem detection accuracy in **I** was 73% for nine sample plots, and it was 73.4% for five sample plots in **III.** So far, these two studies are the only reports on the application of single-scan TLS data in high-density forests with a stem density above 1000 stems per hectare. The results in **I** and **III** indicate that the method developed in paper **I** achieved a stem detection accuracy for dense sample plots that is similar (better in most cases) to that other methods have achieved for sparse plots.

Table 4. Summary of the stem detection accuracy of the single-scan method reported in the previous references as well as **I** and **III**.

	Plot			Result
	number	size	density (stems/ha)	detection (%)
Thies and Spiecker, 2004	1	~30 × 30 m	555.6	22
Maas *et al.*, 2008	3	15 m radius	212–410	86.7–100
Strahler *et al.*, 2008	1	50 m radius	130	40.2
Brolly and Kiraly, 2009	1	30 m radius	753	62.9–72.3*
Murphy *et al.*, 2010**	18	30 × 33 m or 25 × 40 m	207–570	59
	15	10–20 m radius	153–326	82
Lovell *et al.*, 2011	2	20/50 m radius	124/477	54/68
I	9	10 m radius	509–1432	73
III	5	10 m radius	605–1210	73.4

* Three detection methods were discussed.
** The processing of the TLS data was performed using commercial software. The method was reported in (Bienert et al., 2007). Differences in missing stem detection rates between two stands are due to plot and tree preparation, such as removing undergrowth and small limbs on trees.

In (Lindberg et al., 2012), stem-detection results at the tree level are reported from six sample plots 80 × 80 m in size with a stem density of 519-663 stems/ha. The stem detection rate at the tree level is 45.3%.

The results listed in Table 4 summarize the state-of-the-art research on this topic. However, they should not be understood as a rigorous comparison, as the results depend on the plot/tree attributes, the instrument employed, and processing methods. This concept also applies to the following analyses.

DBH measurement

Table 5 summarizes the accuracy of the plotwise DBH measurements using the single-scan approach, as reported in previous references and **III**.

Table 5. Summary of the plotwise DBH estimation from the single-scan method reported in the previous references and **III**.

	Plot			Result	
	number	size	density (stems/ha)	Bias DBH (cm)	RMSE DBH (cm)
Maas *et al.*, 2008	3	15 m radius	212–410	-0.67 – 1.58	1.80 – 3.25
Brolly and Kiraly, 2009*	1	30 m radius	753	-1.6 – 0.5	3.4 – 7.0
III	5	10 m radius	605–1210	-0.18 – 0.76	0.74 – 2.41

* Three detection methods were discussed.

In **VI**, the DBH estimation results are reported at the tree level from five plots for changed trees. The bias was 0.16 cm, and the RMSE was 1.29 cm. In (Lindberg et al., 2012), the DBH estimation results are reported at the tree level from the above-mentioned six sample plots. The bias of the DBH estimation is 0.16 cm, and the RMSE is 3.8 cm.

DBH estimation results are not reported in other references (Strahler et al., 2008; Murphy et al., 2010; Lovell et al., 2011) or are reported for a subset of all reference trees (Thies and Spiecker, 2004; Pueschel et al., 2013); thus, those studies are not comparable with other studies.

The results in **III** and **VI** indicate that the DBH was estimated for dense sample plots with an accuracy similar (better in most cases) to what has previously been reported for sparse plots.

Tree height measurement

The measurement of tree height using TLS at the plot level has not been thoroughly studied because the visibility of treetops with TLS can be questioned. Previous results have shown that tree height is typically underestimated and that the magnitude of estimation error is typically several meters. In (Huang et al., 2011), a -0.26 m bias and a 0.76 m RMSE is reported for one plot (212 stems/ha) using the multi-scan approach. In (Brolly and Kiraly, 2009), a -0.27 m bias with a 1.82 m RMSE and a -2.37 m bias with a 3.25 m RMSE are reported for one plot (753 stems/ha) using the single-scan approach. In (Hopkinson et al., 2004), an approximate 1.5 m underestimation of tree heights is reported for two plots (465 and 661 stems/ha) using the multi-scan approach. In (Maas et al., 2008), a -0.64 m bias and a 4.55 m RMSE for 9 selected trees on four plots (212–410 stems/ha) are reported using the single- and multi-scan approaches. In (Fleck et al., 2011), a 2.41 m RMSE for 45 selected trees on one plot (392 stems/ha) is reported using multi-scan data. The measurement errors include more underestimations than overestimations.

The direct measurement of tree height is extremely difficult utilizing TLS at the plot level if it is even possible. The reason for the large measurement error lies in both the TLS and reference measurements. The observation of tree tops from the TLS data is possible on sparse sample plots using many scans, as reported in (Huang et al., 2011; Fleck et al., 2011). However, tree height is most likely not directly measurable from TLS data in dense sample plots. Tree tops are most likely shadowed by other parts of the crown in the point cloud, i.e., the wide crowns of tall trees do not allow a nearby scanner to detect the tree tops. A possible solution to the accurate plotwise tree height estimation is the combination of ALS and TLS observations. In such scenario, tree heights are measured utilizing ALS point cloud and the tree positions are estimated using TLS point cloud. This possibility should be studied in future.

The accuracy of conventional reference measurements using a hypsometer ranges from 0.5 m to 1.5 m depending on the tree species (crown type), terrain slope, tree height, and forest density. In addition, tree height measurement using conventional tools assumes that the measurement geometry is a right triangle. However, in practice, this assumption may be invalid when the tree is inclined or the terrain is undulating.

In summary, the magnitude of the estimation error implies that the results of tree height estimation using the TLS method are not yet acceptable for an operational plotwise inventory. More research is needed to investigate the accuracy of TLS-based tree height estimation.

Stem curve measurement

The non-invasive measurement of stem curves using TLS has not been intensively studied. Previous pioneering work included nine pine trees studied in (Henning and

Radtke, 2006) and a single spruce tree in (Maas et al., 2008), in which stem curves were estimated below the lowest living branch. There has been no detailed study of the automatic measuring of the stem curves of different species and different growth stages using TLS as of the time paper **IV** was published.

Stem volume estimation

The developed automated stem volume measurement method was accurate as the best Finnish nationwide allometric volume models (Laasasenaho, 1982). Notably, volume calculations using automated stem curve measurements do not require any predictors. All features were automatically retrieved from the point cloud. In fact, the sampling of tree attributes such as tree height is typically applied on a plot because of the difficulty of accurately measuring tree attributes using conventional measurement tools. Therefore, less accurate estimations can be expected in field inventories using allometric volume models and inaccurate predictors.

There have been no comparable detailed studies of automatic measurements of stem volume on sample plots of different species and different growth stages using TLS as of the time paper **IV** was published.

Stem biomass estimation

Biomass is conventionally measured using biomass equations. Compared with the equations based on DBH and height in (Repola, 2009), biomass estimation using the reconstructed stem model outperformed Repola’s equations. The biomass equations, similar to stem curve equations, are developed using local or national sample data. Therefore, the use of those equations is limited to certain conditions, e.g., the forests that have similar environmental conditions to the sample forests.

More recently, individual tree biomass has also been estimated using ALS data (Popescu, 2007; Räty et al., 2011). The results achieved in **V** gave more accurate estimates than the ALS method. The better estimation accuracy reported in **V** is due to very dense TLS point clouds that allow for a more detailed description of the stem and crown compared to ALS data. The point density of TLS is typically 100–1000 times higher than with ALS. Moreover, the view angle of TLS is more suitable for measuring variation in stem biomass.

There has been no detailed study of automatically measuring the stem biomass of trees of different species and different growth stages using TLS as of the time paper **V** was published.

The multi-single-scan approach

Table 6 summarizes the mapping results of the multi-scan method reported in earlier references. Three to five scans per plot have typically been utilized with the multi-scan method, which is similar to the number used with the MSS method. The stem-detection accuracy using the multi-scan method has been reported as being between 93% and 100% (Simonse et al., 2003; Maas et al., 2008; Murphy et al., 2010; Huang et al., 2011). The mapping results of the MSS method were between 92% and 100%. These results show that the MSS method achieves a mapping accuracy on dense forest plots similar to that of the multi-scan method on sparse plots. In addition, the MSS method achieves this accuracy without point-level registration using reference targets, leading to time savings in forest plot measurements.

The RMSE of the DBH estimation by the MSS method varies between 0.90 cm and 1.90 cm, and the mean bias was 0.47 cm. These results are good, as shown in Table 6. The RMSE of the DBH estimation using the multi-scan method in past studies was between

1.48 cm and 5.69 cm. In theory, the conventional multi-scan method should be superior with respect to the DBH estimation, suggesting that improvements can be made with previously reported multi-scan methods.

Table 6. Summary of the mapping results of the multi-scan method reported in the previous references.

	Plot				Results	
	number	size	density (stems/ha)	scan	detection (%)	RMSE DBH (cm)
Simonse *et al.*, 2003	1	~25 × 25 m	~448	4	92.9	5.69*
Thies and Spiecker, 2004	1	~30 × 30 m	555.6	5	52	–
Henning and Radtke, 2006	1	20 × 40 m	–	15	–	8.9**
Maas *et al.*, 2008	1	12 m radius	309	3	100	1.48
Tansey *et al.*, 2009	1	23 × 21 m	1031	4	–***	1.9 – 3.7
Murphy *et al.*, 2010****	18	30 × 33 m or 25 × 40 m	207 – 570	5	99.6	–
Huang *et al.*, 2011	1	35 × 35 m	212	4	100	3.4 – 3.74

* RMSE is calculated from the mean error and standard deviation of the errors.
** Two trees with the smallest field-measured DBHs were ignored.
*** 100% of the stems that could be identified manually. The overall mapping accuracy was not reported.
**** The processing of the TLS data was performed using commercial software. The method was reported in (Bienert et al., 2007).

Change detection

There has been no detailed study of the detection of changes in forest structure over time using bi-temporal TLS data as of the time paper **VI** was published.

5.2 Feasibility of the developed methods for practical field inventories

The methods developed in this study were designed for plotwise field inventories in boreal forests. The practical requirements of field inventories were taken into account during method development.

The methods that estimate tree attributes work with both single-scan and multi-scan data. The estimation accuracy is expected to be better when using multi-scan data, as the objects are recorded from several directions. A new measurement principle, MSS approach, was also developed. The MSS approach clearly improved the mapping accuracy compared with the single-scan method and increased the applicability of TLS measurements compared with the conventional multi-scan method because artificial reference targets were not needed to aid the registration process.

The applicability of the developed methods was tested in plotwise field inventories. The sample plots consisted of trees at different growth stages and possessed a mixture of species. Both large and small pine and spruce trees were employed in the estimation of stem volume and biomass; the pine trees typically had long, clear trunk and the spruce trees typically had many branches at the lower part of the tree bole. The test data were challenging for the automated processing, but they represent typical and challenging forest conditions that were very close to practical conditions.

These experiment data made possible the discussion of practical issues in the application of TLS in plotwise forest inventories, which have not been discussed in previous works. Those practical topics include, for example, the difficulty of detecting trees that are close to each other, the shadowing effects introduced by trees very close to the scanner, and the poor visibility of trees behind bushes and small trees in the lower canopy layer.

The cost of data acquisition is a very important factor in practical inventories. Several scans per plot are most likely the best data set that can be anticipated in practical plotwise inventories. The single-scan approach must be used when the cost of field data collections needs to be kept down. Several scans per tree in individual-tree studies are not acceptable for practical operations.

Tests in this study were primarily carried out on single-scan data sets. The main idea is to determine what results can be expected at the lowest cost. Meanwhile, the testing of methods that work with single-scan data also paves the way for method development using multi-scan data. The results in this study show that single-scan data are challenging for the estimation of tree attributes because of the significant occlusion effects, especially for dense sample plots. The accuracy of the DBH estimations was, however, similar (better in most cases) to the results obtained from multi-scan data reported in previous research. This result indicates that the methods developed in this study are robust and efficient. The results in this study also show that the methods developed for single-scan data are most likely directly applicable to multi-scan data.

The main objective of this study was to demonstrate the feasibility of TLS in plotwise inventories. Forests in different growing regions have different characteristics because of diverse climatic, geographic, and silvicultural conditions. For example, tree shapes in different climate regions may vary significantly. The methods developed in this study were tested in boreal forests only. The applicability of those methods in other forest types was not discussed and needs further studies.

The methods developed in this study mostly work with 3-D points alone. They are, therefore, intended to be directly applicable to different types of scanners as long as they capture sufficiently dense point clouds. The data sets collected by TLS instruments vary between different measuring principles and manufacturers. Some data are captured only by certain scanners, such as intensity at a particular wavelength, color, and/or waveform. The application of those data in data processing may yield significant benefits, but the associated algorithms are bound to certain hardware. 3-D points are the most basic data captured by TLS, and they are available in all TLS data sets. Methods that work with 3-D points alone are widely applicable as far as the hardware is considered.

In contrast, if TLS can provide a point cloud that describes the volume of a tree based on point cloud geometry, the solution is universal and there is less of a need for national allometric models. The general use of allometric models can thus be questioned.

Altogether, the experiments indicate that TLS measurements have the potential to be applicable in practical plotwise inventories in boreal forests.

5.3 Feasibility of the developed methods for forest-related studies

The methods in the original papers were developed for plotwise forest field inventories. Meanwhile, the methods are also applicable to other forest-related studies.

The modeling method in this study was concentrated on the tree stems. The method can also be utilized to build the whole tree model with some modifications. Automated detection of branch position is discussed in (Henning and Radtke, 2006). Individual branches can, therefore, be processed as though they were individual tree stems as long as the point cloud is sufficiently dense. This applies to both coniferous and deciduous trees. Individual tree models can be used in many studies, including 3-D canopy structure, visual reality, and CO_2 release estimations. Currently, the decomposition process of woody tree issue is estimated using average branch size, e.g., several centimeters. The proposed method would allow the direct modeling of tree branches with different sizes. This detailed model could thus provide more accurate CO_2 release estimates. Similarly, the change detection method proposed for plotwise inventories is also applicable to the detection of tree-level structure changes after some modifications.

The developed methods are also directly applicable to the development and update allometric models. Such studies can clearly benefit by using the new techniques. At the moment, national allometric models are developed using sample plots distributed across the country and destructive measurements. For example, in (Repola, 2009), biomass equations were developed based on 908 pine trees and 613 spruce trees collected in 77 stands all over Finland. This method is expensive, labor intensive, and time consuming.

The results of this study indicate that automatic estimates of stem volume using point clouds are quite accurate and that stem biomass is highly correlated to the estimated volume. The stem volume is also clearly correlated to some other biomass components, such as bark and total biomass, as reported in (Kankare et al., 2013). Therefore, allometric models may be established using automated measurements from point clouds. This possibility would be highly interested in counties where there are no excellent data sets measured destructively and in cases destructive measurement is forbidden such as city forests. The automated measurements reduce both the cost of data collection and the damage to forests, which is economical in both ecological and economic senses. In addition, the trees or plots documented in a point cloud can be used in future and in other studies, so that the dynamic changes can be studied and the number of data sets increases all the time, whereas destructive work can be performed only once.

5.4 Further developments

The new methods and techniques developed in this study, as well as the new information brought into the research field, provide the basis for further developments.

First, the new methods may introduce new field measurement principles.

A permanent sample plot in national forest inventories is typically a small area of forest with a radius of approximately 10 m. However, a large sample plot is desirable in practice because it provides a more accurate and comprehensive understanding of the forest environment and makes the registration of the ground reference and airborne or space-borne RS data easier. Using conventional measurement methods to collect reference data on circular plots with radii larger than 10 to 12 m is very demanding and mostly impractical for forest inventories, especially if the stem count per hectare is high.

The experiments in **III** indicated that nearby scans can be automatically matched by applying an idea similar to that proposed in the MSS method. In this context, nearby scans made within a large area could be matched and transformed into a common system, and field reference data could be collected within a large area.

A large area could also be mapped using only a few scans where each scan has a mapping radius of several dozens of meters. The challenge of this measuring scenario lies in the difficulty of automatically matching two data sets with large radii. The tree locations are used as interest points in the data matching procedure. The common trees between two neighboring scans account for approximately 50% of all trees in a scan. The percentage of common stems may further decrease as the plot size increases, as the stem-detection accuracy decreases with increasing range in the single-scan approach. However, it is possible to match two data sets with large radii if the detection accuracy does not decrease dramatically at the far end of the plot. Research has shown that trees far from the scanning position can be mapped. The mapping radius was 30 m in the study reported in (Brolly and Kiraly, 2009) and 50 m in (Lovell et al., 2011). An interesting topic is the practical size of a sample plot for mapping a large area using the MSS method. Further research is needed to explore this question. The expense of field forest inventories would decrease dramatically if this idea is proven to be viable.

Second, the new detailed reference data automatically extracted using TLS can also be used to improve the understanding of the forest in large areas. Retrieval of information on individual trees in large areas has been possible using ALS for a decade (Hyyppä and Inkinen, 1999; Hyyppä et al., 2001; Persson et al., 2002). The accuracy of these methods is highly dependent on the quality and quantity of the field reference data. To date, the sample plots and tree attributes, such as the DBH and tree height, have been measured using conventional measurement tools. It is, however, possible to train the ALS point cloud metrics for area-based variable prediction using more tree attributes obtained directly from TLS point clouds, such as stem volume and biomass. Accurate tree-level data from sample plots combined with individual-tree-based inventories will result in highly accurate forest inventories in the future.

Third, the application of TLS data and automated processing techniques offers new possibilities for improving forest management activities. TLS data and automated processing provide detailed stem quality information at the tree level, such as the stem sweep and merchantable length. The costs of such non-invasive measurements are estimated to be less than data collection using a harvester. This information makes it possible to estimate the value of stems based on any desired specification (e.g., market prices). More research is needed to understand the accuracy of stem value estimates in pre-harvest inventories in different forest types and at the tree level. In addition to estimations of stem values, it is also possible to plan the bucking of stems into logs using detailed stem shape data and thereby minimize damage to forest and optimize the overall profit to be obtained. It is important for this optimization to be performed before the trees are felled to enable the planning and maximization of log size and profit at the stand and forest levels. In the future, standing trees, rather than piles of stems in the vicinity of factories, would then serve as wood storage. The forest industry's supply chain can thus be optimized.

More studies of the estimation methods should be also conducted in the future. For example, different regression models have typically been developed for different tree species to estimate volume and biomass because of the differences in stem form and density. In the stem volume and biomass studies using TLS in **IV** and **V**, there were no clear differences between pine and spruce trees. This may be because the automatically reconstructed stem model properly depicts tree shapes. However, this requires further investigation using more samples. Future studies should also aim to further develop the method to estimate other biomass components of trees, such as the crown and total biomass of trees.

The estimation of additional tree attributes should also be studied. For example, tree species is needed information for plot-level and stand-level estimates. TLS data have the potential to determine tree species using either spectrum or waveform data or 3-D points. Investigations should be made into the potential of applying those TLS data to estimate the species of each stem.

Automated point-level registration is another interesting topic. Registration generally comprises three steps, namely, the extraction of feature points, initial translation parameter estimation, and the registration of the point clouds. Automated solutions for certain steps have been reported. With known stem points and initial translation parameters, registration using the cross-sectional centers of the stems was reported in (Henning and Radtke, 2008). The automated extraction of stem points and the cross-sectional centers of stems in dense forest plots using single-scan data were reported in **I**. The estimation of the initial transformation parameters is presented in **III**. A road map of the automated co-registration of several TLS scans at the point level is now available by combining these three studies. The applicability of automatically matching TLS scans of forest plots at the point level should be tested.

Another topic worth further discussion is how TLS should be used in plotwise forest inventories. The discussions so far are based on the assumption that TLS should provide tree attributes in a manner similar to that in conventional field measurement, i.e., all trees on the plot should be measured. In this context, the application of the single-scan approach in dense sample plots does not provide sufficiently accurate results because only approximately 70% of trees are measurable, though the accuracy of the tree attribute measurement itself (e.g., DBH) is actually good. In area-based forest inventories, there is a need to have all trees mapped within the smallest reference unit. However, it is possible to only map a subset of the trees in sample plots when using individual-tree-based forest inventories as long as the selected trees are representative of all trees in the plot. This possibility has recently been discussed in (Lindberg, 2012).

A brand new research direction is to propose, develop, and test a new field measuring protocol using TLS field plots, where only the trees visible in the center scan are considered as references rather than all trees on the plot. This protocol may largely change the landscape of plotwise forest inventories if it works. Discussions should be continued on this topic.

The change detection demonstrated in this study opens up new possibilities for future inventories, for example, the calibration of bi-temporal ALS data. Changes in ALS data could be calibrated using information obtained from TLS in permanent sample plots, and bi-temporal ALS data could be used to map changes over a large area.

More recently, mobile laser scanning (MLS) has been receiving increasing research interest. In MLS measurement, the TLS equipment is mounted on a moving vehicle, such as a skido or an all-terrain vehicle. Both stop-and-go and continuously moving scenarios can be used. The adaptation of a moving vehicle carrying TLS equipment may significantly reduce the time needed to map a single forest plot and increase the size of sample plots. In theory, the techniques proposed and developed in this study for TLS data should be able to be directly employed in MLS data, as the methods use 3-D point cloud data alone and both TLS and MLS produce such data. Research should be conducted to explore such opportunities. In particular, the influence of the positioning accuracy of the vehicle in forest environments should be discussed.

6. SUMMARY AND CONCLUSIONS

The basic hypotheses in this study were that terrestrial laser scanning is capable of documenting forest sample plots in detail, automated mapping methods can provide accurate tree attributes that are measurable or not measurable using conventional field measurement tools, and automated mapping methods can be employed in plotwise forest inventories. The objectives of this study included the development of automated stem mapping methods for plotwise forest inventories and the quantitative analyses of the mapping results. To test the hypotheses and the performance of the developed methods, the experiments were conducted in managed boreal forest in southern and eastern Finland.

The main study area was located in Evo, southern Finland (61.19° N, 25.11° E) and includes approximately 2000 ha of managed forest. Sample plots included trees at different growth stages and of different species. In addition, sample plots were mostly located in dense forests. These conditions represent a challenging forest environment and make the discussion of practical issues possible. Sample plots were scanned as they were. Pre-scan preparations were not performed on any plots. Three commercial TLS instruments were used in the data acquisitions: the Faro LS880HE80 and Leica HDS6000/6100. All of the three scanners use phase-based techniques to measure range at a high accuracy and cover the whole surrounding environment with a dual-axis scanning system. Sample plots were scanned using different scanning scenarios, including single-scan, multi-scan and multi-single-scan approaches.

The results achieved were evaluated using manual field measurements made with conventional measurement tools, manual measurements from the same point cloud data, and destructive measurements in the field and laboratories. In addition, the results were also compared with the results reported in previous references. Bias, RMSE, and RMSE% were used as the main criteria for accuracy.

Automated mapping methods were developed for

- Stem location mapping using the single-scan approach based on both 3-D and 2-D concepts.
- The multi-single-scan mapping approach to improve mapping accuracy and efficiency and to keep the cost of field measurements low.
- Stem curve measurement and the estimation of stem volume and biomass using the automatically retrieved stem curve.
- The detection of forest structure changes using bi-temporal TLS data.

Regarding the quality of the methods, the main results of the study were as follows:

- The stem-detection accuracy was approximately 73% using the single-scan approach in dense forest sample plots. The stem-detection accuracy was 70% to 100% of all visible trees at a distance between 30 m and 60 m using the single-scan approach.
- The stem-detection accuracy was 95.3% using the multi-single-scan (MSS) approach in dense forest sample plots. The RMSE of the DBH estimation ranged from 0.90 cm to 1.90 cm, and the mean bias was 0.47 cm. These results indicate that the MSS method detects tree stems and estimates stem DBH at an accuracy similar to what has previously been reported from multi-scan data, with the difference that artificial reference targets and point-level registration are not required in the proposed MSS method, leading to time savings in forest plot measurements. These results also show that the MSS method improves the mapping results compared with those obtained using the single-scan approach.
- The RMSE of the DBH estimation using the single-scan approach ranged from 0.74 cm to 2.41 cm and the mean bias was 0.35 cm. These results obtained for dense

sample plots achieved a similar accuracy (better in most cases) to those previously reported in references for sparse sample plots.

- DBH was automatically measured with a bias of 0.06 cm and an RMSE of 0.82 cm at the tree level using the multi-scan approach. These results are better than the manual measurements using the same data, which resulted in a bias of 0.58 cm and an RMSE of 1.26 cm.
- The RMSE of the tree height estimation using the MSS method ranged from 2.04 m to 6.53 m and the mean bias was 1.31 m. The RMSE of the height estimations using the single-scan method ranged from 1.36 m to 4.29 m and the mean bias was 0.62 m. The estimation errors for these results are at the same magnitude as those reported in previous publications.
- Stem curves were automatically measured with a mean bias of 0.15 cm and a mean RMSE of 1.13 cm at the tree level for pine and spruce trees. There were no clear differences between tree species.
- The correlations were high between the calculated and field-measured stem volumes when using automated stem curve measurements and when using the existing volume models. For the automated stem curve measurement, a correlation coefficient of 0.99 and an RMSE of 29.29 dm^3 (9.5%) were achieved. For the stem volume models, Model $f(species, dbh, d6, h)$ had a correlation coefficient of 0.99 and an RMSE of 28.92 dm^3 (9.4%), and Model $f(species, dbh, h)$ had a correlation coefficient of 0.99 and an RMSE of 32.72 dm^3 (10.6%). The results obtained show that the measurement of stem volume using TLS data yields an accurate estimate of stem volume using tree attributes that are automatically retrieved and that this approach could be an alternative to stem volume estimation models.
- The reconstructed stem model and the volume estimated from the TLS data correlated highly with the stem biomass (R = 0.98), which was measured destructively. The biomass estimation using the reconstructed stem model outperformed Repola's equations (Repola, 2009), which were based on DBH and height.
- The stem-status-detection accuracy was 96%. The RMSE of the DBH estimation of changed trees was 1.29 cm and the bias was 0.16 cm at the tree level.

The results obtained in this study thus confirmed the initial hypotheses of the study.

The application of TLS data in plotwise forest inventories leads to the accurate measurement of most important tree attributes that are either measurable using conventional tools such as DBH or not non-destructively measurable in conventional field measurements such as stem curve. Meanwhile, the fully automated data processing achieved similar measurement accuracies as manual measurements either using conventional tools and models or measuring from the same point cloud data. The work load and cost of the field measurements can be kept low using automated processing techniques.

There is clearly potential for the application of TLS in plotwise forest inventories. The difficulties of applying the TLS technology lie in highly complicated forest conditions, such as high density, undulating terrain, small trees, and understory vegetation. The potential and challenges need further discussions.

Further studies should explore new protocols for applying TLS in field inventories. Three clear new directions are as follows:

- The integration of detailed tree attributes into large-area inventories, such as training ALS matrices using the stem curves and volumes of individual trees;
- The employment of the TLS field plot in large-area inventories, where only trees visible in the center scan are used as references to train other data sets such as ALS;

- The utilization of large sample plots, either using the MSS method proposed in the study or the mobile mapping technique.

Further studies should also perform additional tests on different sample plots that have different forest conditions and conduct further analyses to investigate the applications for tree-level profit prediction in pre-harvest inventories.

REFERENCES

Antonarakis, A.S., Richards, K.S., Brasington, J., Muller, E., 2010. Determining leaf area index and leafy tree roughness using terrestrial laser scanning. Water Resources Research 46, 1–12.

Aschoff, T., Spiecker, H., 2004. Algorithms for the automatic detection of trees in laser scanner data. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 36, 71–74.

Bienert, A., Scheller, S., Keane, E., Mohan, F., Nugent, C., 2007. Tree detection and diameter estimations by analysis of forest terrestrial laserscanner point clouds. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 36, 50–55.

Brolly, G., Kiraly, G., 2009. Algorithms for stem mapping by means of terrestrial laser scanning. Acta Silvatica et Lignaria Hungarica 5, 119–130.

Bucksch, A., Fleck, S., 2011. Automated Detection of Branch Dimensions in Woody Skeletons of Fruit Tree Canopies. Photogrammetric engineering & remote sensing 77, 229–240.

Bucksch, A., Lindenbergh, R., 2008. CAMPINO—A skeletonization method for point cloud processing. ISPRS journal of photogrammetry and remote sensing 63, 115–127.

Cheng, Z.L., Zhang, X.P., Chen, B.Q., 2007. Simple reconstruction of tree branches from a single range image. Journal of computer science and technology 22, 846–858.

Côté, J.-F., Fournier, R.A., Egli, R., 2011. An architectural model of trees to estimate forest structural attributes using terrestrial LiDAR. Environmental Modelling & Software 26, 761–777.

Côté, J.F., Widlowski, J.L., Fournier, R.A., Verstraete, M.M., 2009. The structural and radiative consistency of three-dimensional tree reconstructions from terrestrial lidar. Remote Sensing of Environment 113, 1067–1081.

Danson, F.M., Hetherington, D., Morsdorf, F., Koetz, B., Allgower, B., 2007. Forest canopy gap fraction from terrestrial laser scanning. IEEE Geoscience and Remote Sensing Letters 4, 157–160.

Dassot, M., Colin, A., Santenoise, P., Fournier, M., Constant, T., 2012. Terrestrial laser scanning for measuring the solid wood volume, including branches, of adult standing trees in the forest environment. Computers and Electronics in Agriculture 89, 86–93.

Erikson, M., Karin, V., 2003. Finding tree-stems in laser range images of young mixed stands to perform selective cleaning, in: Proceedings of the ScandLaser Scientific Workshop on Airborne Laser Scanning of Forest. pp. 244–250.

Fleck, S., Mölder, I., Jacob, M., Gebauer, T., Jungkunst, H.F., Leuschner, C., 2011. Comparison of conventional eight-point crown projections with LIDAR-based virtual crown projections in a temperate old-growth forest. Annals of forest science 68, 1173–1185.

Fonweban, J., Gardiner, B., Macdonald, E., Auty, D., 2011. Taper functions for Scots pine (Pinus sylvestris L.) and Sitka spruce (Picea sitchensis (Bong.) Carr.) in Northern Britain. Forestry 84, 49–60.

Gaffrey, D., Sloboda, B., Matsumura, N., 1998. Representation of tree stem taper curves and their dynamic, using a linear model and the centroaffine transformation. Journal of Forest Research 3, 67–74.

Gorte, B., Pfeifer, N., 2004. Structuring laser-scanned trees using 3D mathematical morphology. International Archives of Photogrammetry and Remote Sensing 35, 929–933.

Haala, N., Reulke, R., Thies, M., Aschoff, T., 2004. Combination of terrestrial laser scanning with high resolution panoramic images for investigations in forest applications and tree species recognition. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 34, 4p.

Henning, J.G., Radtke, P.J., 2006. Detailed stem measurements of standing trees from ground-based scanning lidar. Forest Science 52, 67–80.

Henning, J.G., Radtke, P.J., 2008. Multiview range-image registration for forested scenes using explicitly-matched tie points estimated from natural surfaces. ISPRS Journal of Photogrammetry and Remote Sensing 63, 68–83.

Holmstrom, H., Kallur, H., Stahl, G., 2003. Cost-plus-loss analyses of forest inventory strategies based on kNN-assigned reference sample plot data. Silva Fennica 37, 381–398.

Holopainen, M., Vastaranta, M., Kankare, V., Räty, M., Vaaja, M., Liang, X., Yu, X., Hyyppä, J., Hyyppä, H., Viitala, R., 2011. Biomass estimation of individual trees using stem and crown diameter TLS measurements. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 38, 91–95.

Hopkinson, C., Chasmer, L., Young-Pow, C., Treitz, P., 2004. Assessing forest metrics with a ground-based scanning lidar. Canadian Journal of Forest Research 34, 573–583.

Hosoi, F., Omasa, K., 2006. Voxel-based 3-D modeling of individual trees for estimating leaf area density using high-resolution portable scanning lidar. IEEE Transactions on Geoscience and Remote Sensing 44, 3610–3618.

Huang, H., LI, Z., Gong, P., Cheng, X., Clinton, N., Cao, C., Ni, W., Wang, L., 2011. Automated methods for measuring DBH and tree heights with a commercial scanning lidar. Photogrammetric engineering and remote sensing 77, 219–227.

Huang, P., Pretzsch, H., 2010. Using terrestrial laser scanner for estimating leaf areas of individual trees in a conifer forest. Trees 24, 609–619.

Hyyppä, J., Inkinen, M., 1999. Detecting and estimating attributes for single trees using laser scanner. The photogrammetric journal of Finland 16, 27–42.

Hyyppä, J., Kelle, O., Lehikoinen, M., Inkinen, M., 2001. A segmentation-based method to retrieve stem volume estimates from 3-D tree height models produced by laser scanners. IEEE Transactions on Geoscience and Remote Sensing 39, 969–975.

Jupp, D.L.B., Culvenor, D.S., Lovell, J.L., Newnham, G.J., Strahler, A.H., Woodcock, C.E., 2009. Estimating forest LAI profiles and structural parameters using a ground-based laser called “Echidna®”. Tree Physiol 29, 171–181.

Kankare, V., Holopainen, M., Vastaranta, M., Puttonen, E., Yu, X., Hyyppä, J., Vaaja, M., Hyyppä, H., Alho, P., 2013. Individual tree biomass estimation using terrestrial laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing 75, 64–75.

Keightley, K.E., Bawden, G.W., 2010. 3D volumetric modeling of grapevine biomass using Tripod LiDAR. Computers and Electronics in Agriculture 74, 305–312.

Laasasenaho, J., 1982. Taper curve and volume functions for pine, spruce and birch (Pinus sylvestris, Picea abies, Betula pendula, Betula pubescens). Finnish Forest Research Institute.

Lappi, J., 2006. A multivariate, nonparametric stem-curve prediction method. Canadian Journal of Forest Research 36, 1017–1027.

Lefsky, M., McHale, M.R., 2008. Volume estimates of trees with complex architecture from terrestrial laser scanning. Journal of Applied Remote Sensing 2, 023521–023521–19.

Li, R., Weiskittel, A.R., 2010. Comparison of model forms for estimating stem taper and volume in the primary conifer species of the North American Acadian Region. Annals of forest science 67, 16p.

Liang, X., Litkey, P., Hyyppa, J., Kukko, A., Kaartinen, H., Holopainen, M., 2008. Plot-level trunk detection and reconstruction using one-scan-mode terrestrial laser scanning data, in: International Workshop on Earth Observation and Remote Sensing Applications, 2008. IEEE, pp. 1–5.

Liang, X., Litkey, P., Hyyppä, J., Kaartinen, H., Kukko, A., Holopainen, M., 2011. Automatic plot-wise tree location mapping using single-scan terrestrial laser scanning. The photogrammetric journal of Finland 22, 37–48.

Lindberg, E., 2012. Estimation of canopy structure and individual trees from laser scanning data (Doctoral thesis). Swedish University of Agricultural Sciences, Umeå.

Lindberg, E., Holmgren, J., Olofsson, K., Olsson, H., 2012. Estimation of stem attributes using a combination of terrestrial and airborne laser scanning. European Journal of Forest Research 131, 1917–1931.

Litkey, P., Liang, X., Kaartinen, H., Hyyppä, J., Kukko, A., Holopainen, M., 2008. Single-scan TLS methods for forest parameter retrieval, in: SilviLaser 2008. pp. 295–304.

Lovell, J.L., Jupp, D.L.B., Culvenor, D.S., Coops, N.C., 2003. Using airborne and ground-based ranging lidar to measure canopy structure in Australian forests. Canadian Journal of Remote Sensing 29, 607–622.

Lovell, J.L., Jupp, D.L.B., Newnham, G.J., Culvenor, D.S., 2011. Measuring tree stem diameters using intensity profiles from ground-based scanning lidar from a fixed viewpoint. ISPRS Journal of Photogrammetry and Remote Sensing 66, 46–55.

Maas, H.G., Bienert, A., Scheller, S., Keane, E., 2008. Automatic forest inventory parameter determination from terrestrial laser scanner data. International Journal of Remote Sensing 29, 1579–1593.

Moorthy, I., Miller, J.R., Berni, J.A.J., Zarco-Tejada, P., Hu, B., Chen, J., 2011. Field characterization of olive (Olea europaea L.) tree crown architecture using terrestrial laser scanning data. Agricultural and Forest Meteorology 151, 204–214.

Murphy, G.E., Acuna, M.A., Dumbrell, I., 2010. Tree value and log product yield determination in radiata pine (Pinus radiata) plantations in Australia: comparisons of terrestrial laser scanning with a forest inventory system and manual measurements. Canadian Journal of Forest Research 40, 2223–2233.

Neubert, B., Franken, T., Deussen, O., 2007. Approximate image-based tree-modeling using particle flows. ACM Transactions on Graphics (TOG) 26, 88.

Persson, A., Holmgren, J., Söderman, U., 2002. Detecting and measuring individual trees using an airborne laser scanner. Photogrammetric engineering & remote sensing 68, 925–932.

Petrie, G., Toth, C.K., 2009. Terrestrial laser scanners, in: Topographic Laser Ranging and Scanning: Principles and Processing. pp. 87–128.

Pfeifer, N., Gorte, B., Winterhalder, D., 2004. Automatic reconstruction of single trees from terrestrial laser scanner data, in: Proceedings of 20th ISPRS Congress. pp. 114–119.

Pfeifer, N., Winterhalder, D., 2004. Modelling of tree cross sections from terrestrial laser scanning data with free-form curves. International Archives of Photogrammetry, remote sensing and spatial information sciences 36, 76–81.

Popescu, S.C., 2007. Estimating biomass of individual pine trees using airborne lidar. Biomass and Bioenergy 31, 646–655.

Pouliot, D.A., King, D.J., Bell, F.W., Pitt, D.G., 2002. Automated tree crown detection and delineation in high-resolution digital camera imagery of coniferous forest regeneration. Remote Sensing of Environment 82, 322–334.

Pueschel, P., Newnham, G., Rock, G., Udelhoven, T., Werner, W., Hill, J., 2013. The influence of scan mode and circle fitting on tree stem detection, stem diameter and volume extraction from terrestrial laser scans. ISPRS Journal of Photogrammetry and Remote Sensing 77, 44–56.

Puttonen, E., Litkey, P., Liang, X., Kaartinen, H., Kukko, A., 2010. Single Tree Canopy Projection Area Extraction from Single-scan Terrestrial Laser Scanner Data, in: Silvilaser 2010. pp. 54–64.

Repola, J., 2009. Biomass equations for Scots pine and Norway spruce in Finland. Silva Fennica 43, 625–647.

Reshetyuk, Y., 2009. Self-calibration and direct georeferencing in terrestrial laser scanning (dissertation). Royal Institute of Technology, Stockholm, Sweden.

Rojo, A., Perales, X., Sanchez-Rodriguez, F., Álvarez-González, J.G., Gadow, K. von, 2005. Stem taper functions for maritime pine (Pinus pinaster Ait.) in Galicia (Northwestern Spain). European Journal of Forest Research 124, 177–186.

Räty, M., Kankare, V., Yu, X., Holopainen, M., Vastaranta, M., Kantola, T., Hyyppä, J., Viitala, R., 2011. Tree biomass estimation using ALS features, in: SilviLaser 2011. pp. 16–20.

Seidel, D., Beyer, F., Hertel, D., Fleck, S., Leuschner, C., 2011. 3D-laser scanning: A non-destructive method for studying above-ground biomass and growth of juvenile trees. Agricultural and Forest Meteorology 151, 1305–1311.

Shlyakhter, I., Rozenoer, M., Dorsey, J., Teller, S., 2001. Reconstructing 3D tree models from instrumented photographs. IEEE Computer Graphics and Applications 21, 53–61.

Simonse, M., Aschoff, T., Spiecker, H., Thies, M., 2003. Automatic determination of forest inventory parameters using terrestrial laserscanning, in: Proceedings of the ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests. pp. 252–258.

Strahler, A.H., Jupp, D.L.B., Woodcock, C.E., Schaaf, C.B., Yao, T., Zhao, F., Yang, X., Lovell, J., Culvenor, D., Newnham, G., 2008. Retrieval of forest structural parameters using a ground-based lidar instrument (Echidna®). Canadian Journal of Remote Sensing 34, 426–440.

Tansey, K., Selmes, N., Anstee, A., Tate, N.J., Denniss, A., 2009. Estimating tree and stand variables in a Corsican Pine woodland from terrestrial laser scanner data. International Journal of Remote Sensing 30, 5195–5209.

Thies, M., Pfeifer, N., Winterhalder, D., Gorte, B.G.H., 2004. Three-dimensional reconstruction of stems for assessment of taper, sweep and lean based on laser scanning of standing trees. Scandinavian Journal of Forest Research 19, 571–581.

Thies, M., Spiecker, H., 2004. Evaluation and future prospects of terrestrial laser scanning for standardized forest inventories. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 36, 192–197.

Watt, P.J., Donoghue, D.N.M., 2005. Measuring forest structure with terrestrial laser scanning. International Journal of Remote Sensing 26, 1437–1446.

Watt, P.J., Donoghue, D.N.M., Dunford, R.W., 2003. Forest parameter extraction using terrestrial laser scanning, in: Proceeding of the ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests September. pp. 2–4.

Wezyk, P., Koziol, K., Glista, M., Pierzchalski, M., 2007. Terrestrial laser scanning versus traditional forest inventory First results from the polish forests. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 36, 424–429.

Wiant, J.H., Spangler, M.L., Baumgras, J.E., 2002. Field Note-Comparison of Estimates of Hardwood Bole Volume Using Importance Sampling, the Centroid Method, and Some Taper Equations. Northern Journal of Applied Forestry 19, 141–142.

Xu, H., Gossett, N., Chen, B., 2007. Knowledge and heuristic-based modeling of laser-scanned trees. ACM Transactions on Graphics (TOG) 26, 19.

Yang, Y., Huang, S., Trincado, G., Meng, S.X., 2009. Nonlinear mixed-effects modeling of variable-exponent taper equations for lodgepole pine in Alberta, Canada. European Journal of Forest Research 128, 415–429.