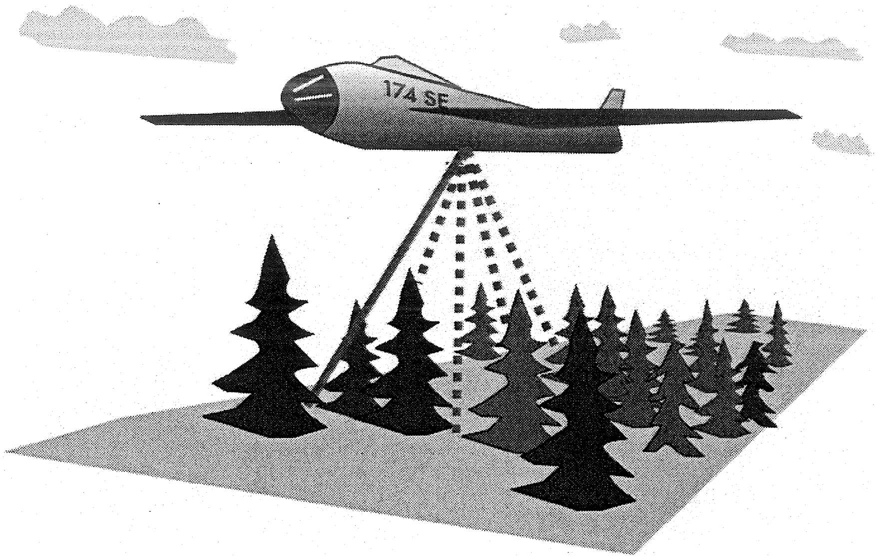
Proceedings of the
ScandLaser Scientific Workshop
on Airborne Laser Scanning of Forests



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[1] Moved from Session 2 due to change in programme

[2] Moved from Poster Session due to change in programme

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FOREWORD

Modern airborne laser scanners can make up to 80 000 precise measurements per second for 3D-positions on the ground and in vegetation canopies. Furthermore, laser scanning technology is still rapidly improving. Given the latest research, laser scanning obviously has great potential as a tool for estimating forest resources and describing forest environments.

The title of the workshop - ScandLaser - is short for "**Scand**inavian workshop on **Laser** scanning of forest resources". It started with a small informal workshop in Umeå, May 2002, with participants from Finland, Norway, Sweden and Canada. It was then apparent that the Scandinavian countries had complementary experiences in this research field. In Finland several projects related to analysis of single trees detected in laser scanner data are ongoing. Much of this work started in the EU project HighScan, coordinated by Helsinki University of Technology. In Norway, on the other hand, laser scanning of forest resources on stand level has been taken to a stage where it is nearly operational. In Sweden cooperation between the Swedish Defense Research Agency (FOA) and SLU for laser scanning of forest resources began in1991 and has continued to this day. Further details about the laser scanning experiences in Finland, Norway and Sweden are given in the "country reports" in this volume.

At the meeting in May 2002, it was obvious there was a need for a more widely announced scientific meeting. We received funding from SNS (the Nordic Forest Research Co-operation committee, http://www.nordiskskogforskning.org), which is the main economic sponsor of ScandLaser. The meeting could serve a dual purpose: *i)* to inform and discuss what could currently be done practically in laser scanning of forest resources; and *ii)* to discuss current scientific issues in this rapidly developing field. Therefore, we decided to organize both a "Practical workshop" to be held September 2, 2003, and a "Scientific workshop", to be held September 3-4, 2003. With one exception, this proceedings volume includes only the contributions to the Scientific workshop.

EARSeL (the European Association of Remote Sensing Laboratories, http://www.earsel.org) helped in organizing the scientific workshop, which is also the first activity of the new EARSeL Special Interest Group (SIG) on forestry. Further information about this special interest group can be obtained from Håkan Olsson (Hakan.Olsson@resgeom.slu.se). Furthermore, the workshop is also announced as an activity within IUFRO division 4 (http://www.iufro.org/).

To our knowledge, the ScandLaser scientific workshop in Umeå is the first meeting of its kind in Europe. In 2002, there were two similar meetings organized: *The Australian Workshop on Airborne Laser Altimetry for Forest and Woodland Inventory and Monitoring*, and the *International Workshop on Three-dimensional Analysis of Forest Structure and Terrain using LiDAR Technology*. The main results from these workshops are being published in a special issue of the Canadian Journal of Remote Sensing, appearing Autumn 2003. We are happy to provide continuity from these workshops by having one of the editors of the special issue, Dr. Mike Wulder, as one of the key note speakers. Dr. Wulder and Dr. Paul Treitz, who is a member of the ScandLaser scientific committee, were also organizers of the Canadian workshop. Another key note speaker is Dr. Randolph Wynne from Virginia Polytechnic who gives an overview of forestry laser scanning in the USA. He is also the guest editor of a recent (June 2003) Forest Science special issue on forestry remote sensing. We are also pleased to have Dr. Ove Steinvall, head of the department of laser systems at the Swedish Defense Research Institute, as a key note speaker. Dr. Steinvall was a pioneer in laser scanning and he is uniquely positioned to provide the forestry community with insights about what future technology to expect.

This proceedings volume is printed in time to be distributed at the workshop, and only the abstracts are peer reviewed. The reason for this is that we think this quickly developing field merits fast communication. A digital version of the proceedings, with illustrations in color, as well as the power point presentations from the practical workshop, will be made available at the EARSeL SIG Forestry home page: http://www-earsel-sig-forestry.slu.se/scandlaser. Furthermore, a few selected articles from the scientific workshop are likely to be published in the Scandinavian Journal of Forest Research, after peer review.

TheScandLaser workshops have been organized jointly between the Swedish University of Agricultural Sciences (SLU), the Agricultural University of Norway (NLH) and the Finnish Geodetic Institute (FGI), with Håkan Olsson at SLU as chairman of the local organizing committee; Erik Næsset at NLH, as responsible for the Practical workshop, and Juha Hyyppä at FGI, as chairman of the scientific committee. Members in the local organizing committee have been Tina Granqvist Pahlén and Heather Reese, and members in the scientific committee have been Paul Treitz, Queens University; Mats Nilsson, SLU; Håkan Olsson, SLU; and Erik Næsset, NLH.

It is our hope that ScandLaser will help create a forestry laser scanner community in Europe, with links worldwide. Looking forward, one timely follow-on to ScandLaser will be the International Conference *"Laser-Scanners for Forest and Landscape Assessment – Instruments, Processing, Methods and Applications"*, which will be held in Freiburg, Germany, 3 – 6 October 2004. (http://www.natscan.de).

Håkan Olsson, Juha Hyyppä and Erik Næsset

LASER SYSTEMS FOR VEGETATION AND TERRAIN MAPPING – A LOOK AT PRESENT AND FUTURE TECHNOLOGIES AND CAPABILITIES

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ABSTRACT

We are living in a three-dimensional (3 D) world and the potential to capture this world by 3 D laser radar systems will revolutionize many military and civilian applications. This paper will discuss some of the recent laser radar technologies of relevance for vegetation and terrain mapping.

Exiting development is taking place concerning 3 D sensing focal plane arrays (FPAs). With these devices a full range and intensity image can be captured in one laser shot. For laser radars (lidars) this will lead to more accurate positioning of the different pixels relative to each other and also to higher resolution and area coverage. The demands on scanning will also be much reduced.

Laser sources are developing towards ultra short pulse lengths (sub nanoseconds) and tunability in wavelength. Scanner and beam forming is moving towards a non-mechanical function using optical phased arrays. Finally development in signal processing is rapid concerning the use of 3 D information for automatic object detection, classification and identification. Fusion between laser radar and other sensors for example multi and hyper spectral sensors is also beginning to show interesting results. This paper will describe 3 D imaging activities at FOI and give example how these data can be used in mapping and other military applications. We will also give examples of the next generations laser radar systems that are predicted to provide cm resolution and operate at full video rate. These systems will be compact and can operate in UAV's.

PRESENT STATUS OF 3 D LASER IMAGING

During the past couple of years there has been an increasing interest in airborne remote sensing using DEM's (Digital Elevation Models) for use in city planning, mobile phone networks, forestry, flood risk assessment, power cable monitoring etc. A number of technologies can be applied to generate DEM's from the well-established aerial photography, interferometric radar and SAR. Airborne laser radar is another technology with great promise. Recently a number of airborne nadir scanning laser radars have been developed for both military and civilian applications, (Steinvall et.al. 1999, Steinvall et.al. 2001) These systems have range resolutions on the order of 10 cm but relatively moderate area coverage rates, in the range 1000-10 000 m^2/s (3.6-36 km^2/h) when opening in a high resolution mode with a 0.25 m spot distance. Technology development in laser sources, scanning techniques and signal processing will probably improve the area coverage substantially and lead to compact systems suitable for new applications, including the use in UAV's. Figure 1 shows performance in area coverage for a typical terrain mapper. From the right part of figure 1 we conclude that an average power of 1 W for an area coverage rate of 100 km^2/h and an altitude of 1000 m. Note that a coverage rate as high as 1000 km^2/h, can be achieved with a laser power as low as 10 W. This is assuming a resolution of 0.25 m per pixel and an operating altitude of 1000 m, if one could realize such a system. The system parameters might be optimistic, for example the sensitivities (1 nW) of the receiver and the assumed reflection of 5% from the tree and ground. However, even if these values are changed towards the negative side we still get moderate average laser powers (< 10 W) for all of the capable systems.

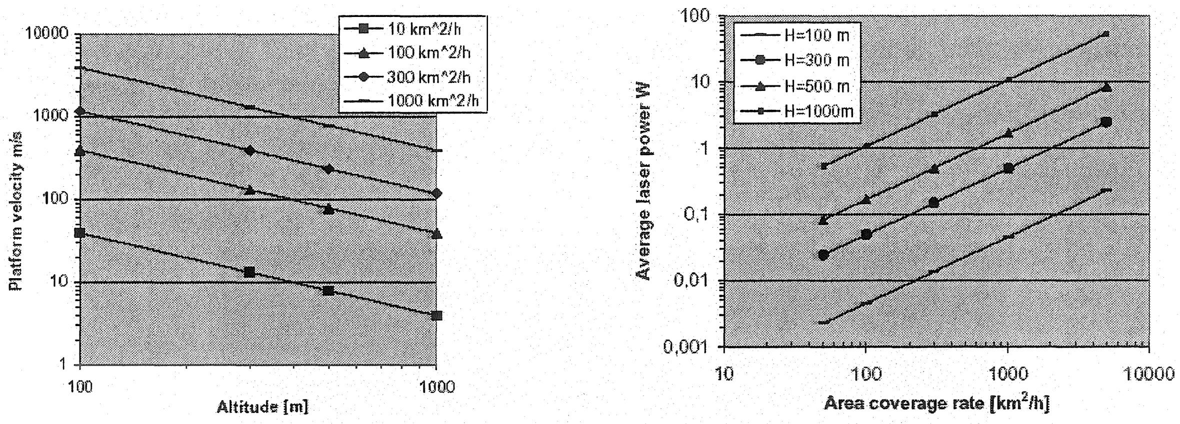


*Figure 1. To the left is a plot of the platform velocity vs. altitude for different area coverage rates. To the right is the average laser power vs. area coverage rates and different altitudes, H. A swath S=0.7*H is assumed together with the laser spot density of 4/ m² for a resolution of d_{res}=0.25m.*

For future airborne applications, for example using unmanned airborne vehicles (UAVs), the laser power may not be the most critical factor. More critical are the scan rate and the difficulty to realize a high velocity scanner for 5-10 cm post aperture scanning. Rotating scanners, such as polygon and rotating wedges, will have enough speed. However, they will not be efficient in distributing the laser shots. On the other hand, a detector array may use simple mechanical scanners and will have a very even shot distribution on the ground, which clearly is an advantage when processing the data.

There are about half a dozen or more commercial systems for airborne terrain and vegetation mapping, for example TopEye (Sweden), Airborne Laser Terrain Mapper (ALTM, Canada), Topo-Sys (Germany) and some others. Recently Leica entered the market with an airborne scanning laser radar (ALS 50, se figure below).

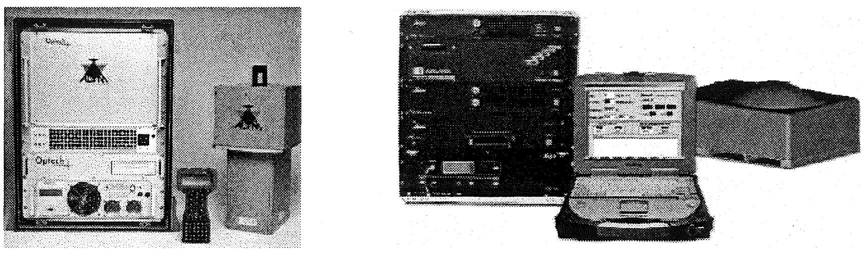


Figure 2: Example of a commercial lidar for airborne terrain mapping, ALTM from Optech, Canada and ALS 50 from Leica.

These systems typically can deliver both range and intensity data for multiple returns. So far full digitization of each return waveform has not been common but the technology now permits this to be made up to 70 kHz in prf. Sampling at a bandwidth of 1 GHz or better gives the time history of each shot of value for data quality and refined processing. Intensity maps will allow for terrain and object classification besides range only data. The ability to record the gain of the receiver subsystem at the time of each laser shot is of great help in post processing and to normalize intensity values to reflectivity information taking the flight altitude and slant range into account.

For underwater applications we have SHOALS (Canada), Hawk Eye (Sweden) and LADS (Australia) as examples of commercial systems for depth sounding. The pulse energy for depth sounding greatly exceeds that of land mapping why the rapid scanning need is not as critical as for the land case. Array detectors, however, offer a better transverse resolution of interest for detecting small objects in the water (like mines). The activities in airborne laser scanning started at FOI with the depth sounding application (the FLASH system, (Steinvall 1996)).

Figure 3 gives examples of data generated by the FLASH-system. The laser pulse repetition rate (PRF) for this system is limited to 200 Hz. Today systems with a prf up to 3-10 kHz are being developed for depth sounding. Such systems will be much more capable and useful in future UAV:s as they are designed for unassisted operations. The combination of depth sounding and terrain mapping is natural, as is including high resolution modes for better under-water target detection and classifications.

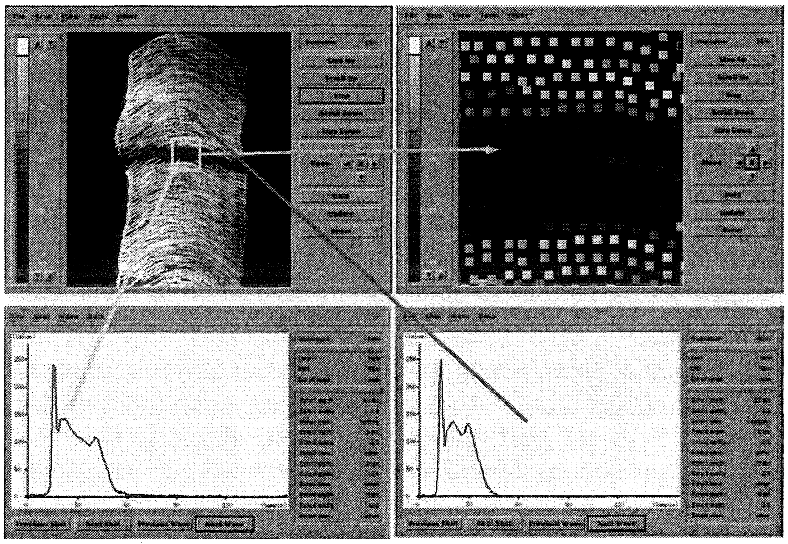


Figure 3. Example of depth sounding data from the FLASH-system developed at FOI. Above left a real time sweep color coded for depth (2-7 meters in this example) and above right a zoom in the data where each pixel corresponds to one laser shot. The lower shows the waveforms from the log amp showing the steep surface marker followed by the backscatter and the bottom peak.

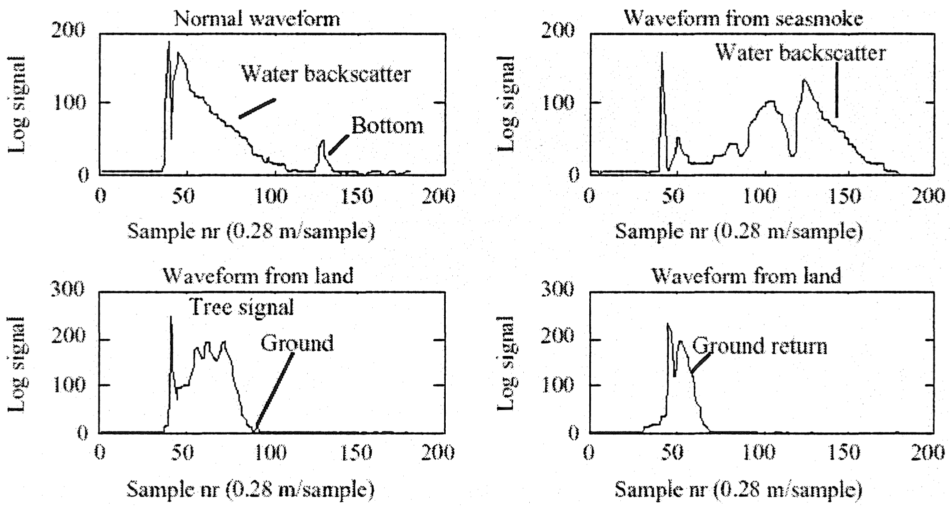


Figure 4. Example of waveforms from the FOA FLASH system. The waveforms are from water indicating bottom, from sea smoke and water and 2 examples from land, with trees and without. The sharp peak in the beginning of the waveform indicates the position of the water surface and has no relevance over land.

At FOI we are developing tools to handle laser data to form realistic synthetic environments for military planning, sensor and electronic warfare simulation. We combine these data with IR and aerial photography to form very realistic synthetic environments as can be seen from figure 5. A good deal of this data fusion process and object classification is automatic.

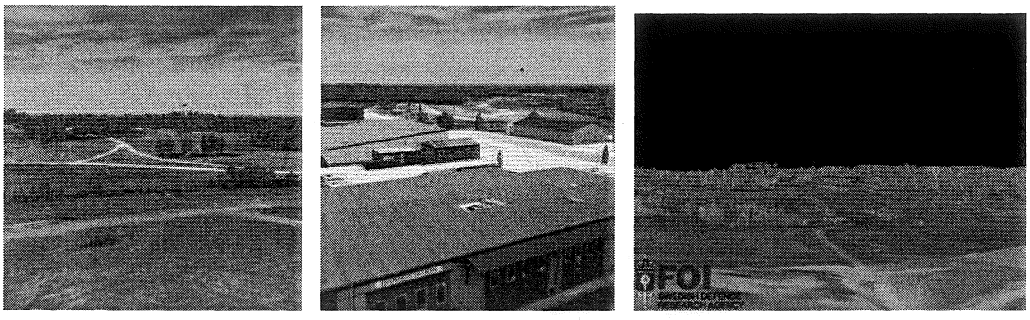


Figure 5. Synthetic scenes in 3 D, generated by data from airborne scanning laser radar (Top Eye). The 3 D data is fused with the texture from aerial photographs. The right image shows a synthetic IR scene. Images by FOI.

There is a growing interest and use of land based 3 D laser radars for geoscience and industrial use. Example of systems developed for this purpose are ILRIS 3 D (Optec Canada), RIEGL (Austria), Zoller and Fröhlich (Germany) and Cyrax (US). In the civil an field, scanning 3 D laser radars are used for engineering, construction, operations and maintenance activities in the manufacturing plant and civil/survey markets. They are also used for architectural, virtual reality, heritage preservation, forensic, and other applications. In the military field, they are used for signature and 3 D data collection to build accurate 3 D models. At FOI we are using the RIEGL scanner (wavelength 0,9 μm) and also the ILRIS scanner at 1.5 μm. These instruments have cm resolution but suffers from relatively low scene update limited by the single detector and moderate prf (1-10 kHz). If they could have a more rapid update they should be of interest for automation of the forest industry for example in unmanned ground vehicles for both cutting and remote classification of the trees.

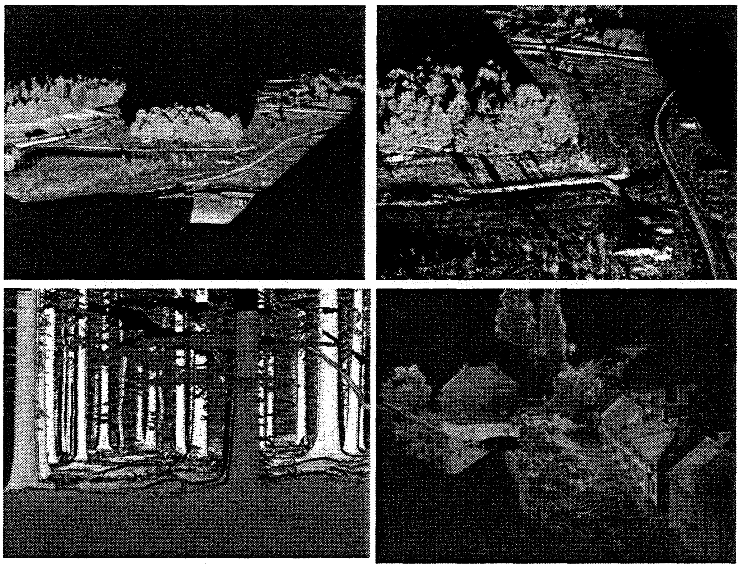


Figure 6. The above show 3 D data from the ILRIS scanner taken from the roof top lab at FOI Linköping. One scene has been scanned and two different projections are seen. The maximum range is about 3-800 meters depending on scene reflectivity. The resolution is in the cm level in range. Below left shows a close up image of trees taken with the ILRIS and right a combined laser scan and color image of "Old Linköping" obtained from the RIEGL scanner.

At FOI we are using range gated viewing for long rage and difficult target imaging. By sliding with the range gate in steps as short as 1 ns, we can obtain 3 D imagery from a series of 2 D images. A potential application for forestry is illustrated in figure 7. Over a wide FOV images from several range gates are collected. Each range slice image corresponds to a certain height above ground. The drawback with this method is that high power pulsed lasers have to be used and that the time between pulses has to accommodate with the speed of the aircraft. Future 3 D FPA will make this gating procedure unnecessary. Figure 8 shows example of range gated imagery obtained at FOI. Image intensifier tubes for eye safe lasers at 1,5 μm have been developed by the US company Intevac.

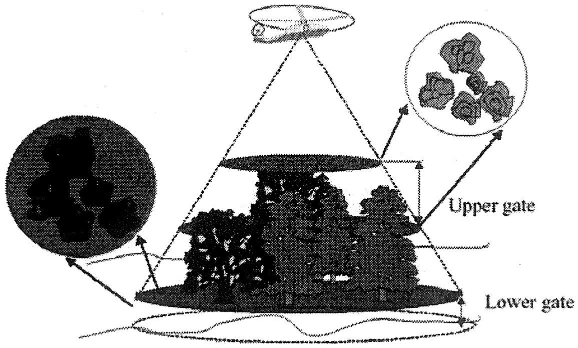
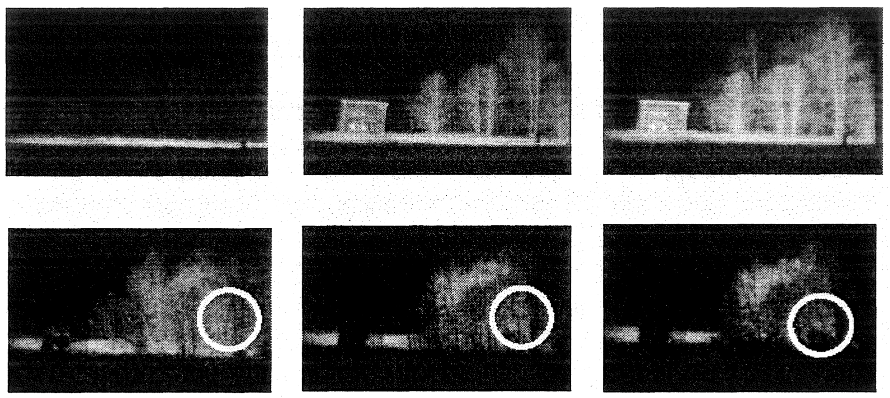


Figure 7. Principle of range gated imaging applied to forestry.



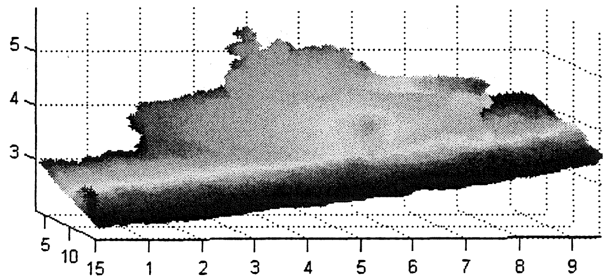


Figure 8. Above different 2 D images at different start for the gate, using a pulsed laser and a time controlled image intensifier. Below generating 3 D data for a tank from range gated images. Images FOI.

NEW TECHNOLOGY

This section will shortly describe recent progress in detector, laser and scanner technology of interest for compact sensors for remote sensing of forests and for mapping in general. There are several concepts for scanner less 3 D laser radar systems for reconnaissance and other applications. These are:

- FM/CW approach using a modulated laser and a "self mixing FPA"Range gating systems with short range gates
- Modulated gain tube and modulated laser
- Streak camera tube
- Flash imaging FPA, with photodiodes (avalanche or unity gain diodes) or FPA with an intensified tube for gain improvement

The technology which seems to draw the largest attention in 3 D imaging for military applications just now is 3 D sensing focal plane arrays (FPAs). Consequently, we will here restrict ourselves to what is believed to be the most interesting technology, the 3 D FPA. For an overview and a description of the other techniques we refer to a recent overview report (Steinvall et.al. 2003).

3 D FPA

The basic principle of the 3 D FPA is illustrated in Figure 8. A laser flood illuminates a target area with a relatively short (1-10 ns) pulse. The time of flight of the pulse is measured in a per pixel. fashion. The position of the detecting pixel yields the angular position of the target element, and the time of flight yields the range. With a single "laser shot", the complete 3 D image of a target is captured. An important feature to make this type of FPA a reality is to have a readout integrated circuit (ROIC) to capture information that determines the range of a return at each pixel field of view (FOV). In this fashion, though all the 3 D information is captured in an instant, it can be read serially at a rate compatible with passive sensor EO/ IR readout circuits.

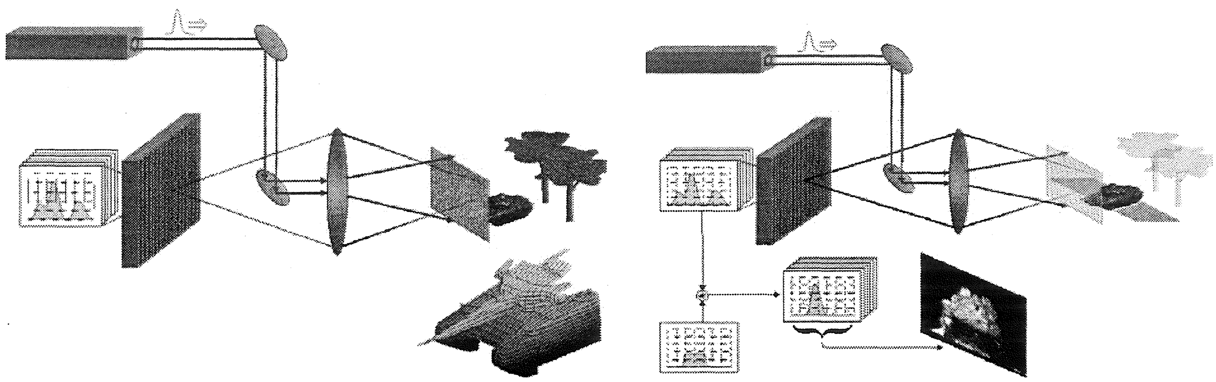


Figure 9. Principle for range gated imaging (left) and 3 D FPA imaging.

There are several reasons why 3 D FPA will revolutionize laser/EO system capabilities. The main reason concerns the sensor design, the improvements in support for automatic target recognition (ATR) and other application areas. The sensor design and use of the sensor will be improved due to the fact that each image is retrieved within nanoseconds. This means that there will be no blurring of the image due to platform vibrations, a whole scene is captured in one exposure and scanning is not necessary for small FOV imaging. There are moderate scanning demands for systems with large area coverage. The 3 D FPA will enable integrated true active/passive imaging and multifunctional systems.

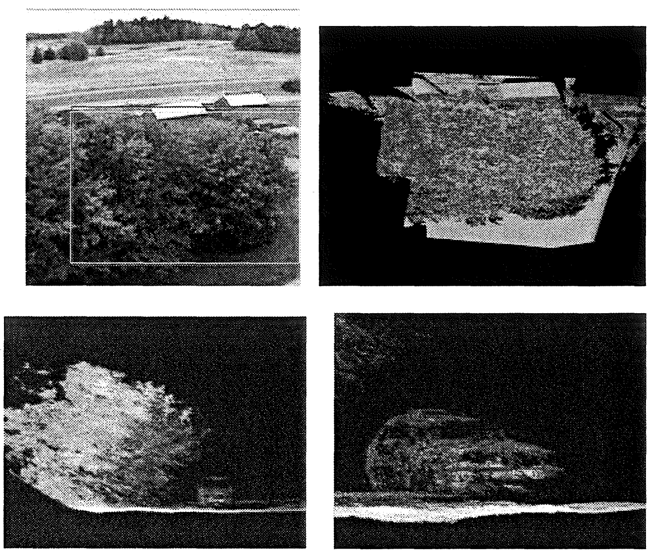


Figure 10. Look behind the trees and bushes. 3 D imaging gives stunning results. Images FOI.

Automatic target recognition (ATR) will be improved. As a rule of thumb, 200 pixels per target at 15-20 cm range resolution and 40 cm cross range resolution is needed for robust ID of military targets like vehicles (Zheng, 2001). This will be possible to achieve with one exposure of the scene. Due to the fast retrieval of high resolution range images (<10-20 cm), ATR will have new capabilities as:

- Reduction of false target rate and missed objects, compared to current ATR technology FPA sensor data allows robust template matching and object recognition and fingerprinting, as dimensions are measured down to the cm level.
- Detection and recognition of "hard" targets is possible in bad visual conditions.
- "See" through smoke, fires, camouflage or 80-90 % vegetation coverage.

Applications where the FPA technique will improve the functionality by:

- facilitate UGV (UAV) navigation through terrain (or close to ground).
- facilitate UGV (UAV) in route planning
- increasing the capability for high resolution terrain mapping

Several companies and research organizations in the US are developing 3 D FPA (Steinvall, 2003). In Europe developments are taking place in UK, France and Germany.

Lincoln Laboratory has an integrated program to develop technologies and address system issues relevant to 3-D laser radars. Technology development efforts include the development of silicon Geiger-mode APD arrays with associated timing circuitry, the development of InGaAs Geiger-mode APD arrays to expand the sensitivity of these devices to the short-wave IR, micro Nd:YAG laser development, and ladar prototype systems development. Figure 11 illustrates the circuit and operation for Geiger mode APD arrays.

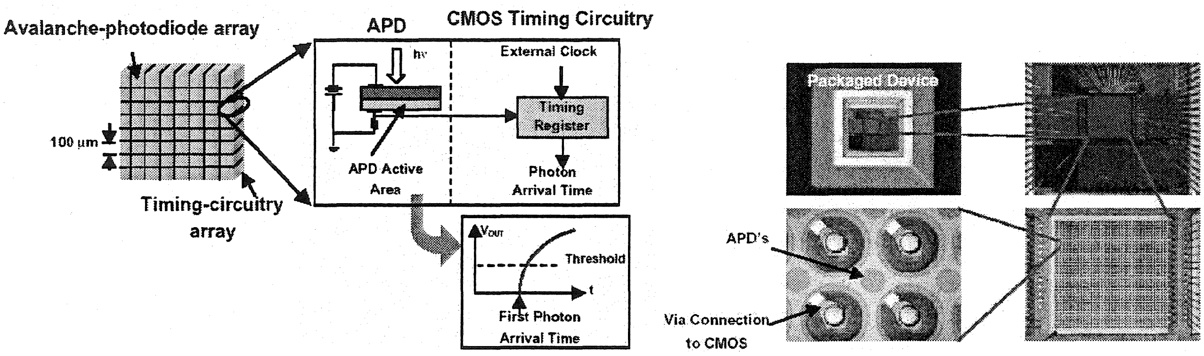


Figure 11. Illustration of the circuit and operation of a detector working in the Geiger mode. (Heinrichs , 2001).

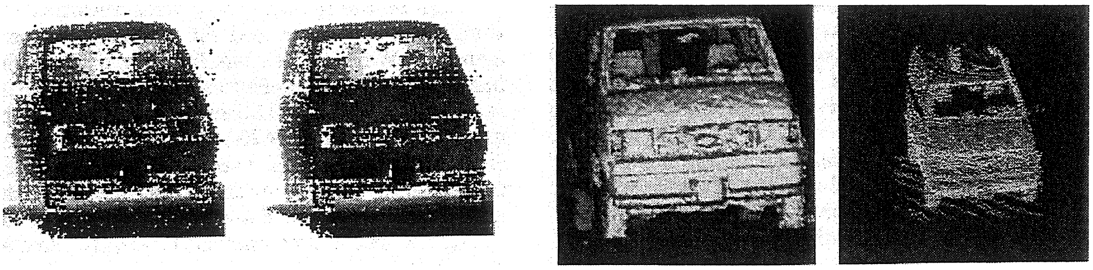


Figure 12: Image of a Chevrolet Astro obtained by the MIT 3 D laser radar. From left to right: Single frame of target at 60 meter during a sunny day with only 3 microJ pulse energy, 3 frame average , next two rendered images from multiple frames. (Albota, 2003).

Raytheon, Advanced Scientific Concepts and others are developing 3 D FPA with full waveform capturing capability leading to both range and intensity and the time history of the return. The MIT approach leads to a very sensitive device (photon counting capability) but with range only readout.

Laser technology

The demand on lasers for terrain mapping might be summarized as:

- Have a short pulse or modulation giving a high range resolution and a high range accuracy
- Having enough pulse energy enabling a flight altitude in the 3-500 m range (at least).
- Enabling a high area coverage rate
- Eye safe emission for people on the ground looking into the beam.
- Be compact, efficient and reliable.

Several types of lasers come into consideration such as diode lasers, solid state diode pumped lasers especially µ-chip lasers and fiber lasers. Recent development in fiber laser (IPG Photonics 2003) have realized lasers with short pulses and up to 100 kHz in prf. The fiber delivery, excellent beam quality, rugged design and air cooling make them very attractive for airborne lidar. The emitted power at the wavelength (1,06 µm) is available up to 20 W at 10 % power efficiency.

Microchip lasers are pulsed (typically at 10 kHz), may be considered quasi-cw (continuous wave) and, due to their small size, low cost, and superb beam quality, suitable for many of the existing pulsed laser classes traditionally filled by actively Q-switched YAG lasers. The µchip laser can be pulsed with very short (sub ns pulse widths).

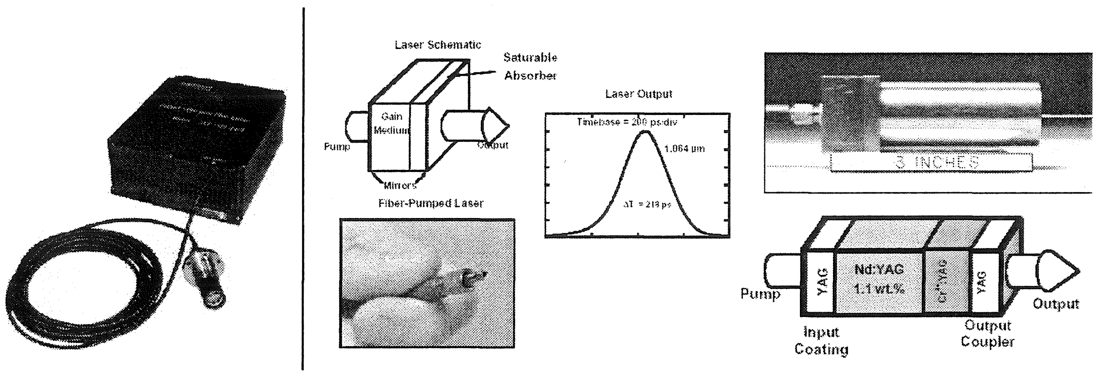


Figure 13. Left a fiber laser from IPG Photonics and right microchip lasers developed by MIT Lincoln Laboratories.

Lasers can also be tuned to other wavelength regions by optical parametric conversion and other techniques. Of special interest might be multi-wavelength lidars emitting RGB or emitting 0.26, 0,53, 1,06 and 1,55 μm simultaneously. The last option can be made with 3 crystals pumped by a single Nd:YAG laser source.

Scanning and beam forming technology

3 D FPA will in a longer perspective eliminate the need of scanner as one may see push-broom linear arrays similar to those made for passive EO sensors. However until very large arrays are developed some type of scanning will be needed. Today scanning is often done with large mirrors (5-20 cm) in front of the T/R-module. Programmable scanners (Axelsson,1990) let the scan mode adaptively be adjusted to the proper task, e.g. to generate an optimal semicircular scan patterns for a search mode and increase ground resolution when hovering from a helicopter for example There is a practical limit for post-telescope scanners depending on size. For a 20 cm aperture the scan frequency may be 20-30 Hz at the most for scanning ± 20°.

Fibers can not only be used for distributing laser and received optical power but may also be used to transform beams to different shapes and to scan from simple circular scans shapes to rectangular raster scans. Scanning can also be done using optical lenslet arrays, which are moved relative to each other, deflecting a passing beam. According to Ricks (Ricks and Willhite, 1997), the microlens array scanner can be 3 times faster than a galvanometer for the same field of regard and using 2.5 % of the drive power in addition to being much smaller and lighter. Such scanners are also considered for use on cars and for handheld laser radars.

New interesting non-mechanical concepts of scanning/pointing are under development, for example using the liquid crystal (LC) spatial light modulator (SLM) device and micro-mirrors. Electronic focusing and beam shaping as well as multi-beam capability are very attractive features for these devices (Hård, 1999).

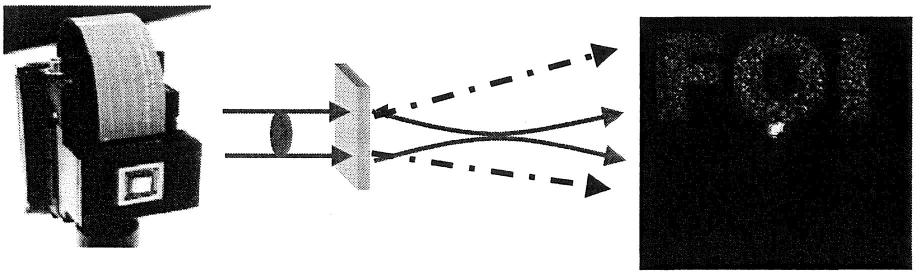


Figure 14. Non mechanical beam steering and beam shaping using a liquid crystal spatial light modulator (SLM). Images FOI.

FUTURE SYSTEMS CONCEPTS

There should be no doubt that high resolution laser radars will play a very important role for remote sensing of forests in the future. In this section some concept ideas will be discussed.

As the goal for most data collecting sensor is to move quickly and accurately from measured data to information the fusion between passive EO cameras more in agreement with the human visual system and laser radar data seems natural.

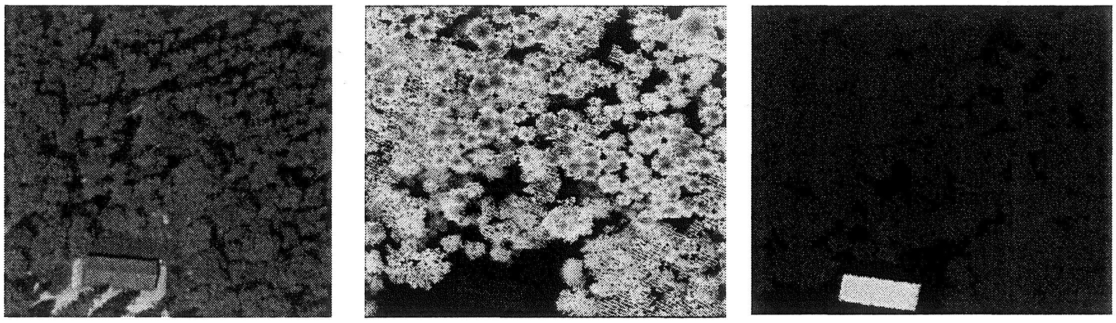


Figure 15. Left photograph, middle color coded height and right classified scene (ground, trees, and building). Future sensor may do this automatically and also sens different species and their stress stage. Images FOI.

Lasers will give high resolution 3 D images in different wavelength bands to detect, classify and measure individual trees and sense the vegetation status by measuring fluorescence to reveal their condition. Individual trees can be detected using high density airborne laser scanner data. Also, variables characterizing the detected trees such as tree height, crown area, and crown base height can be measured (Persson et.al. 2002, Holmgren et.al. 2003, Hyyppä et.al. 2001). The shape of the time resolved return is a strong indicator for object shape (Steinvall, 2000) of interest for high altitude sensing.

Adding a passive multi/hyper spectral EO cameras and/or a multi wavelength laser will improve classification for trees but also for other type of vegetation and man made objects. There seem to rather limited work in this area so far. Fluorescence can be used to monitor vegetation stress (Weibring et.el. 2003). For this application spectral and time resolved response is of importance. A multi-slit streak tube imaging lidar (MS-STIL) concept has been demonstrated to provide a number of different fluorescent, multi spectral, and hyper spectral imaging modalities. In the lidar configuration, the time-resolved aspect of the sensor allows 3D imagery to be collected simultaneously with the spectral data. The ability to measure the fluorescence with high spectral resolution, measure the lifetime of the fluorescent response, and measure the fluorescent response to multiple excitation wavelengths provides a significant number of discriminators for remote species identification and status monitoring (Gleckler et.al. 2001).

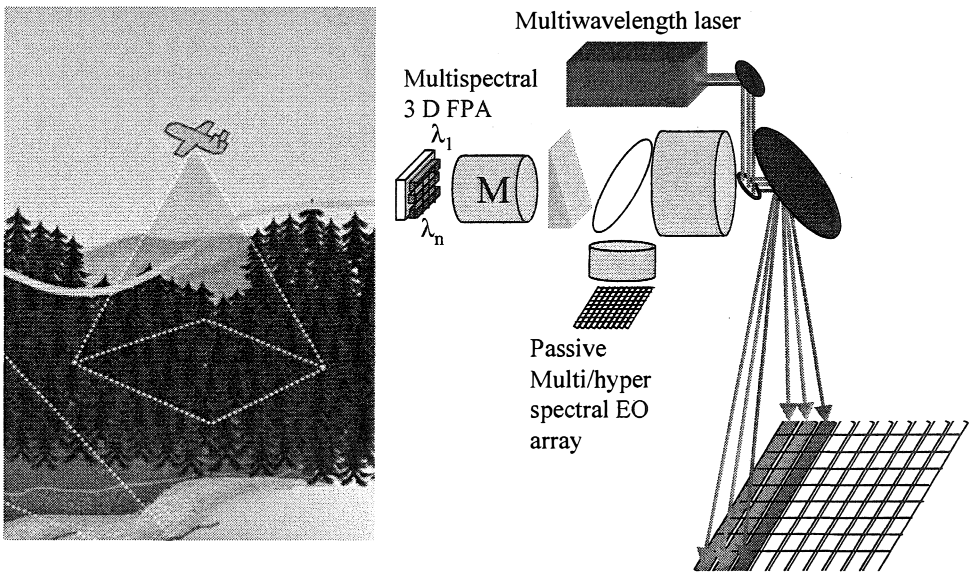


Figure 16. Concept for a future 3 D FPA and passive FPA mutifunction system for remote sensing. The use of an UAV might be an economic way of covering both large and smaller areas. The 3 D FPA provides multiple wavelength 3 D data and the passive camera the visual and IR imagery. If the lens module M is replaced by a streak camera, time resolved fluorescence might be added for vegetation stress monitoring.

Figure 16 shows the concept for a airborne future active/passive remote sensing system. The 3 D FPA might be used for collecting both spatial and spectral information and if M is replaced by a multiple slit streak tube the time resolved fluorescence from the vegetation can be measured.

In the future remote sensing tasks of forests may be performed from unmanned aerial vehicles (UAV:s). This might be economical and also fulfill the UAV-motivating "d:s" – working in a dirty, dull and dangerous mission. Present military laser radar developments for reconnaissance, target ID and weapon guidance are very compact and rely on linear array detectors and high average power and short pulse lasers enabling high coverage rates (100' s of km^2/h) and high resolution (10 cm or better). Figure 17 give some examples of present and future platforms for laser radars. Although civilian remote sensing is a bit different from military applications there should be no fundamental obstacle to make future active/passive remote sensors small and fitting on UAV:s.

CONCLUSIONS

Technology developments in 3 D FPA, streak tubes, new compact multi-wavelength lasers and new scanner/beam forming devices point towards compact versatile laser radars for environmental monitoring. Combining these laser radars with a passive multi or hyper spectral sensor in the same physical package will result in capable and compact systems for both underwater and terrain /vegetation mapping.

Developments for military mapping and surveillance stresses real time processing needs. Many of the methods developed for these systems should be of use in civilian remote sensing and lower the burden in post processing. Military applications also moves towards increased use of unmanned aerial vehicles. If one can solve the problems with flight safety in civilian airspace these UAV systems will also find a place for civilian environmental monitoring.

Figure 17. Above today's platforms for airborne scanning lidars: (Twin Otter for Shoals, ALTM), helicopter (for Top Eye) and Northrop Grumman's unmanned helicopter aimed for carrying US Navy's coastal zone scanning lidar. Below the LOCAAS-a weapon demonstrator program using a scanning laser radar. LOCAAS (Low Cost Autonomous Attack System) is envisioned as a miniature, autonomous powered munition capable of broad area search, identification, and destruction of a range of mobile ground targets (LOCAAS, 2003).

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THE CURRENT STATUS OF LASER SCANNING OF FORESTS IN CANADA AND AUSTRALIA

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ABSTRACT

The large territorial areas of Canada and Australia and the enormous associated information requirements have facilitated the exploration of remote sensing technologies for the characterization of regional and national forest resources. In the spring of 2002 international workshops on light detection and ranging (lidar) remote sensing of forests were held in Victoria, Canada, and near Brisbane, Australia. These workshops were designed capture and communicate the present status of laser scanning of forests. Both workshops, while focused on science and operational applications, had many commercial operators in attendance. The interest and activities of the commercial operators is a testament to the operational utility of laser scanning of forests.

Laser scanning in Australia is considered an operational technique capable of fulfilling specific information requirements. Examples are the use of laser scanning to meet national reporting needs, mapping regional watersheds, estimating carbon, and for forest inventory mapping. The integration of laser data with other complementary remotely sensed data sources has also been investigated.

The collection of laser data for the characterization of forests has a long history in Canada. Early technological limitations have since been overcome and Canada now has strong research and development communities focussed on lidar instruments and related technologies. In Canada there are many companies offering lidar data products (such as canopy height models and digital elevation models) as well as researchers engaged in the development and improvement of forest characterization methods. A key trend emerging from Australia and Canada, where characterization of large areas is common, is the use of lidar as a sampling tool.

In this communication, a summary of the current state of laser scanning of forests in Canada and Australia is presented.

INTRODUCTION

Laser altimetry or light detection and ranging (lidar) is an active remote sensing technology that measures differences in time from the emission of a laser pulse from a sensor to the interception of the laser pulse by target objects in the path of the laser. Using the speed of light, these time measurements can be converted into distance or range (see Lim et al. 2003a for overview). Applications of scanning lidar systems have developed recently through parallel advances in global positioning systems and inertial navigation systems. The result being an opportunity to use lidar systems to characterize forest structure and underlying terrain. Canopy height models are now routinely generated, providing valuable information on a range of vertical forest attributes (St-Onge et al. 2003). The generation of quality terrain models is required to ensure accurate vegetation height estimation. Realistic terrain models are also sought as an aid to forest engineering activities as well as management planning (such as exclusion of riparian areas). Lidar remote sensing of forests and terrain are applications areas that are benefiting from rapid advances in computing hardware and software, instrumentation, and the post-processing of lidar point data into useful information. Lidar data provides for rapid and accurate characterization of a range of forest characteristics.

The ability to use lidar data to accurately characterize both terrain and forest structure has led to a high commercial interest in the technology. Opportunities to augment or supplant existing approaches for generating similar information with lidar may be possible, resulting in an interest in lidar technology and applications from a wide range of groups. Technology developers have an interest in ensuring that applications exist to utilize their products. Value added geomatics companies have an interest in ensuring that applications and methods generate information in an accurate manner. The research community plays a key role in the development of robust applications.

Workshops are an ideal medium to facilitate communication amongst these groups. Since many of the algorithms for producing information on forest canopies are predicated on an accurate rendition of the underlying terrain surface. Therefore, the inclusion of terrain in workshops ostensibly designed for forest monitoring audiences is useful. Given that the majority of forest management agencies are mandated with both engineering and inventory responsibilities, the simultaneous extraction information on terrain and canopies, enables inter- agency economies to be gained.

Australia and Canada share many characteristics that have resulted in a similar evolution in the use of laser data for the characterization of forests. Both are large nations with correspondingly large reserves of natural resources. In the case of Canada, nearly half of the country is forested. In Australia, forests are less ubiquitous; nonetheless they are a coveted ecosystem. Australian forests harbour a wide and unique range of flora and fauna and the climate enables highly productive plantation forestry. The responsibility for stewardship of natural resources is mandated at the provincial or state level in both countries.

The development of lidar instruments and the applications of lidar data in Canada and Australia are difficult to encapsulate in a brief summary. The laser altimetry field is growing quickly, including an ever increasing number of researchers and practitioners. As a result, the goal of this communication is to attempt to summarize some of the emerging trends of lidar remote sensing in Canada and Australia. The material captured in this paper is based upon the results of an international collaboration between Australian and Canadian researchers and near concurrent workshops. Due to space limitations, not all presentations will be specifically mentioned; the communications items mentioned below provide access to source information from the workshops.

The international nature of the workshops, and of lidar research in general, has resulted in the inclusion of some activities occurring outside Canada and Australia in this overview. Specific topics addressed are: advances in lidar instrumentation; the commercialization of lidar technology and information; advances in terrain and forest applications; and the utility of lidar for both industrial forest management and as a sampling tool for regional characterization. In addition, indications of future directions resulting from the identified trends and workshop recommendations will also be discussed.

WORKSHOPS

Canada

The "Workshop on Three-Dimensional Analysis of Forest Structure and Terrain Using LiDAR Technology," was held on March 14th and 15th in Victoria, British Columbia, Canada. The goal of the workshop was to have experts in lidar remote sensing of forests share their knowledge and experiences with each other and with the user community. Participants included over 80 representatives from government research organizations, universities, and the forest industry. Also in attendance were developers of lidar sensors. Canada is at the global forefront in lidar system development (e.g. Optech) and associated hardware (e.g. Applanix). The workshop was chaired by Drs Benoît St-Onge, Paul Treitz, and Mike Wulder.

Australia

The "Australian Workshop on Airborne Laser Altimetry for Forest and Woodland Inventory and Monitoring," was held April 18th and 19th , 2002, in Brisbane, Queensland, Australia. The two day workshop was generously supported by the Bureau of Resource Sciences, Queensland Department of Natural Resources, and Queensland Environmental Protection Agency. Attended by over 50 scientists, managers, and policy makers, it provided an excellent opportunity for integration between lidar technologists, applications developers, and end users. The workshop was chaired by Phil Norman and Christian Witte.

Communications

Each workshop selected differing information sharing mechanisms. The Canadian Workshop has a website where relevant materials, such as talk abstracts and links are collected[3]. The Australian Workshop produced a compact disk including presentation materials and synthesis documents. To combine the outcomes of both workshops, a special Issue of the Canadian Journal of Remote Sensing, was produced. With lidar remote sensing being a relatively nascent field, the subjection of lidar research to peer review is an important stage in the evolution of the field. The goal of the journal special issue is to capture the latest developments utilizing lidar remote sensing for the characterization of forests and terrain. An on-line edition of the special issue[4] will be available in late September, 2003; with the regular issue being available in mid-October, 2003. This internationally gathered special issue captures the flavour of the Australian and Canadian workshops. In order to attract state-of-the-art submissions, contributions were not limited to research presented at either workshop. The 12 papers selected for inclusion in the special issue represent a broad spectrum of the challenges faced when using lidar data to characterize forests and terrain.

INSTRUMENTATION

Airborne

The plans for improving airborne lidar instruments include development of enhanced hardware that is smaller in size and consumes less power. The development of integrated flight management systems that include components such as real-time swath plotting are key to increasing the functionality of lidar. Increasing potential flying altitudes is also a goal of hardware developers, as high flying altitudes enable wider swaths; however, problems emerge as more power is required and eye-safety issues may result. Having image swaths correspond to camera fields-of-view may enable a single overpass resulting in multiple data products that are then suitable for integration. The latest instrument available from Optech[5], the global leader in laser instrument development, is the ALTM 30/70. It is capable of 70,000 (Hz) postings per second (at elevation up to 1200 m). The laser repetition rate can be adjusted to different rates (33, 50, and 70 kHz). It can also operate at altitudes of up to 3000 m, which enables a 2800m swath width, at a laser repetition rate of 33 kHz. The ALTM 30/70 can also operate in a waveform mode, and can come with an integrated 4000 x 4000 pixel metric frame digital camera for geo-referenced (X,Y,Z) colour or colour-IR images with sub-pixel accuracy. Horizontal accuracy is reported as better than 1/2000 of flying altitude, vertical accuracy is reported as 15 cm at 1200 m and 35 cm at 3000 m.

Several areas under development by sensor manufacturers include increases in repetition rates, and sensor integration with co-registered imagery (such as the new Optech instrument). As waveform capture is now available; related analysis techniques should be given higher research priority if this new information is to be capitalized upon. Improved methods for determining ground surface height beneath dense canopies are also required. Intensity information is currently not well understood and is subsequently underutilized in the analysis of lidar data. Sensors with an option for user specification of beam divergence (e.g., wide or narrow) depending on application will also be useful. Increases in swath width have been made, allowing for improved matching with a co-registered imager. Regarding processing of lidar data, improvements to block adjustment, classification algorithms, and object identification, are all desired by the user community and require additional development.

Lidar instrument developers also foresee software development needs. Efficiency is a goal, with the availability of x, y, z data within hours of landing being desired. Opportunities for software / hardware integration for specific applications are also being explored. To encourage software and algorithm development integration of data with 3rd party software, utilizing an open data format, is also sought after. There is also a trend emerging that has lidar data providers custom manufactur-

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[3] Canadian Lidar workshop: http://larsees.geog.queensu.ca/lidar/LiDAR_Workshop/lidar_workshop.html

[4] CJRS Special Issue: http://pubs.nrc-cnrc.gc.ca/cjrs/cjrs.html

[5] Optech: http://www.optech.on.ca/

ing instruments from component parts, for instance the ALMIS-350 of Mosaic Mapping, Ottawa, Ontario.

Ground Based

Besides the Riegl 3D scanning instruments, developed in Austria, Optech has developed the ILRIS system, and CSIRO has develop the ECHIDNA. Ground based laser instruments have shown promise in applications such as the measurement of tree height, DBH, and foliage amount. The ability to link the ground based measurements to airborne collected lidar data presents a range of possibilities, including calibration and validation of airborne lidar derived attributes. In addition to the collection of forest mensurational data, ground based laser instruments may be useful for providing simulation and model inputs.

Satellite

Large footprint airborne lidar instruments, such as SLICER and LVIS, have operated as a test-bed for future satellite based lidar. The Vegetation Canopy Lidar (VCL) was initially slated for launch in 2000 (Dubayah et al. 1997). The VCL was intended to be a space-based large-footprint system. The launch of the sensor has experienced delays, with the rescheduled 2004 launch questionable. There is currently sufficient funding to get the lasers to work, with no additional funding currently identified by NASA.

With the low probability of a VCL launch, the now orbiting Geoscience Laser Altimeter System (GLAS), aboard Ice, Cloud and land Elevation Satellite (ICESat), provides some potential for structural characterization of Australia and Canada. While the instrument was designed to measure ice-sheet topography and associated temporal changes, operation of GLAS over land and water will provide along-track topography. GLAS is nadir viewing, and uses Nd:YAG laser with 1064 and 532 nm output, with 40 pulses per second. The centres of the 70 m footprints are separated in the along track direction by 170 m from a 600 km altitude orbit. The cross track resolution is determined by the 183 day ground track repeat cycle which results in 15 km track spacing at the equator and 2.5 km at 80 degrees latitude. GLAS data may be used in conjunction with optically derived land cover or structural attributes such as LAI. Potential attributes are maximum height, height, depth, and relative plant area by three strata (under-, mid-, and over-storey). Vegetation applications are currently under investigation. For additional details on the mission, see Zwally et al. (2002).

COMMERCIAL SECTOR

Globally, there has been significant increase in lidar related activity since 1995. Currently, there are more than 75 companies and over 60 sensors. The market is dominated by small footprint, time-of-flight sensors. Additionally, it is estimated that 60% of commercial activity is DEM generation. In general, the commercial lidar market in Canada and Australia may be considered as immature, with great growth potential. Even though the markets are nascent and emerging, there are multiple vendors with a range of systems available. The applications are also evolving. The lack of standards associated with lidar has been identified as an impediment to the widespread use of the technology. For example, purchasers are interested in buying products, i.e. a canopy height model, or DEM, without having to know the inner workings of lidar collection and processing. As a result, there is a need for industry to transfer its focus away from creating data and towards the creation of products. To facilitate the reduction of costs associated with lidar data and the creation of standardized products, several research priorities have been identified for the commercial sector: Efficiency bottlenecks; Automated sensor calibration; Efficient automated feature extraction; Development and integration of new techniques in sensor design; Availability of software tools; and Training.

With costs often described as a factor limiting use of lidar data, efficiencies and improvements that result in improved products at a lower cost are highly desirable.

Data Costs

Lidar data costs are based upon a combination of characteristics, including sensor availability, fixed costs for the data provider, cost control by the client, product definition, and subsequent price model. These characteristics are summarized below:

1. Sensor availability costs related to:
    a. Geographic location.
    b. Time of year.
    c. Scheduling (length of advance notice to data provider).
        1. Scheduling flexibility may allow for negotiation of a lower price.
    d. Survey size (length of time senor required).

2. Fixed costs for data provider:
    a. Capital equipment (depreciation).
    b. Survey costs (≈10 to 20% of costs).
    c. Aircraft.
    d. Ferry time to acquisition area included.
    e. Fuel.
    f. Field crew.
    g. Overhead (i.e. insurance, warranty on sensor, profit).

3. Cost control for client:
    a. Optimize use of capital asset (partners, purchase in volume).
    b. Match data requirements to data specifications (do not purchase unnecessarily high postings).
    c. Provide own ground support.
    d. Do data processing in-house.
    e. Product definition.
    f. What is required, posting, survey area, data characteristics, ancillary data (intensity, GPS observable).
    g. Price models are often based upon a fixed base price, ferry time to site, acquisition time, and variable costs based upon requested survey parameters (Table 1). The resultant costs are closely tied to the nature of the data requested.

Table 1. Expected costs for lidar data for a range of postings from 30 to 150 centimetres. The posting is the interval of the spacing of lidar hits that is expected for a particular configuration of aircraft location and sensor specification. For larger postings or larger projects, pricing will decrease, for instance, with a large project and large postings, industry pricing may be as low as $115/sq. km.

Posting (cm)	Price / Ha (CDN$)	Price / sq. km (CDN$)
150	5.9	600
90	9.8	1000
30	19.3	1900

Lidar Survey

A successful collaboration with a commercial data provider is dependent upon attention to detail in project planning. Included in project planning is the management of scope and schedule. Scope is related to ensuring that there is a clear link between information needs and data collected. Cost control is linked to scope management and flexibility in acquisition. Additionally, partnering opportunities can result in cost sharing. Many different groups have needs for elevation data. These needs can be used to form a consortium.

Consortia

A means for reducing lidar costs, is to develop partnerships for data and cost sharing. There are examples in the US Pacific North West, with the Puget Sound Lidar Consortium[6], and in Australia with the Southern Murray-Darling Basin LIDAR Project. The latter project is understood to be the largest lidar project in the southern hemisphere, at a total area of 1.8 million ha. The range of agencies that can be included are interested in, for instance, natural resource management, hazard management, and utilities. In general, it is the shared interest in highly detailed elevation data that enables development of a data acquisition and processing partnership.

CHARACTERIZING TERRAIN

In the forest monitoring community, terrain is an attribute frequently required to meet a range of information needs. With road building being one of the highest cost activities in forest management, terrain data is a valuable information source. Often, engineering needs will enable a lidar survey that can in turn be utilized for vegetation purposes.

Example terrain needs in the forestry context include:

- Estimating area eligible for harvest (e.g. mask out ineligible areas, such as steep slopes);
- Erosion monitoring;
- Contractor payouts;
- Environmental audit compliance;
- Net harvested area audit;
- Road layout (harvest planning);
- Identification of rock outcrops, cliffs;
- Road / stream update;
- Field navigation;
- Canopy attribute estimation;
- Error in bare earth surface model leads to errors in canopy;
- Image rectification; and
- Ortho-photos, satellite images.

To improve processing speed and consistency, surface generation techniques should be as automated as possible. There are a range of approaches that are generally applied in surface generation: block minimum algorithms, minimum-roughness algorithms, and no-multiple return algorithms. Block minimum algorithms are fast, but can be biased on low slopes. Minimum-roughness algorithms require no horizontal surface assumption, but do need user definition of a spike tolerance. To improve DEM generation, the time stamp on the returns can be utilized, double coverage can be flown (or a greater pulse density). In instances where the terrain is primary attribute sought, the area can be flown in leaf-off condition. Much of the time in generating elevation data is still spent undertaking manual vetting and correction. As a result, fully automated classification is desirable to avoid unspecified biases and to also control costs. The use of spatial information is recommended to improve terrain elevation models (Haugerud and Harding 2001). Leaf area index can be used as an indicator of when a reduction in ground strikes may occur.

Terrestrial ecosystem maps are another product of interest developed from terrain data. Currently, in Canada, terrestrial ecosystem maps are required to represent large areas. As a result, the use of lidar data has been limited due to the associated large volumes of lidar data and inherent high cost (in generating data with superfluous detail for this particular application). With terrestrial ecosystem mapping focussed on large areas, the detail inherent to lidar data is superfluous noise that may occlude the extraction of landscape level processes. Hierarchical mapping and analysis approaches may be required to mitigate these issues.

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[6] Puget Sound Lidar Consortium: http://duff.geology.washington.edu/data/raster/lidar/

Riparian mapping is also an important application enabled through the development of lidar terrain models. Riparian mapping is used to identify harvest exclusion zones and / or inventory of the species found in the riparian areas. The integration of lidar and multispectral video data can allow for vegetation of uniform heights but different species composition to be grouped appropriately (visually, using the video). Problems faced when assigning floristics to riparian species may be related to within tree variations resulting in mapping of separate classes. Again, areas with dense canopies may not have sufficient ground returns to facilitate identification.

Terrain models developed from lidar are generally more accurate than those from air photo interpretation. Terrain is also somewhat invariant over time. The integration of photogrammetric and lidar data and techniques has been explored to investigate means for capitalizing upon the benefits of both softcopy photogrammetry and lidar data. A comparison of softcopy photogrammetry and lidar can be found in Baltsavias (1999). The synthesis of softcopy photogrammetry and lidar allows for numerous uses of terrain information with historic and future aerial stereo photos. For instance, canopy surface elevation can be reconstructed from stereo aerial photos using softcopy photogrammetry, the lidar bare earth elevation can then be subtracted, and the result is the canopy surface height for any set of aerial photos (St-Onge and Achaichia 2001). Historic photo pairs may be processed to benchmark forest stand conditions. Benchmark survey conditions may be compared to current conditions to assess growth and yield, impacts of disturbances, and forest productivity.

MEASURING FOREST ATTRIBUTES

Forest inventory in both Canada and Australia are under the stewardship of non-federal jurisdictions. Canadian provinces and Australian states have the responsibility for forest management. Special programs may exist for comprehensive national monitoring programs, but the management of forest resources remains a provincial / state responsibility.

In general, consistently good results in estimating forest structural attributes (at stand level) using both large- and small-footprint systems, have been found. The following are example inventory attributes where lidar measurement success has been found:

- Height and various height derivatives;
- Canopy cover;
- Above-ground biomass;
- Volume; and
- Stocking.

Inventory

The accurate estimation of terrain and canopy characteristics has led to operational agencies attempting to develop comprehensive monitoring systems based upon lidar data. For instance, a forest inventory system has been developed by the Alberta Research Council (ARC). The goal of the forest management system is to undertake image and lidar pre-processing, object segmentation, and attribute assignment to the objects generated. High quality DEM are envisioned to provide for landform/soil mapping, landslide hazard assessment, stream/riparian area identification, forest engineering applications, and terrain visualization. The forest management system is being developed to deal with issues such as an extensive land base, natural stand variability, variability in managed stand density, and variability in forest productivity. In order to address these issues, a number of challenges are faced, from instrumentation through to processing. These issues include sensor alignment, accuracy of sensors and calibration, minimizing ground control (direct georeferencing), and fully automated processing. The end result is a synergy of lidar and image data for developing automated forest inventory. The ARC system parameters of interest include tree type, tree height, crown diameter, wood volume, and tree age class.

Forest structural characteristics with small-footprint lidar may be measured at the stand and plot level. Efforts are on-going to develop the capability using lidar data to estimate plot features, such as: height, canopy cover, basal area, cubic volume and tree biomass (Means et al. 2000).

Using a regression based approach, additional models were developed for stocking density and a stand density index. This estimation approach requires training using ground truth data and may not be transportable (empirical). In addition, there is a risk of model over-fitting.

Data Integration

Individual tree isolation techniques are well established in Canada (Gougeon 1995; Hill and Leckie 1999) and Australia (Culvenor 2002). The integration of lidar with multispectral data is a logical next step in the evolution of using individual tree isolation to characterize forests (Leckie 1990). The characterization of vertical structure using lidar is unique information that is not well captured by multispectral data. When combining individual tree isolation with lidar data, either data source may be considered as the primary input. For instance, lidar attributes can be assigned to objects developed from the multispectral data, multispectral attributes may be assigned to the objects generated from the lidar, or the data analysis can combine the two, such as using the height information to guide the multispectral analysis (by creating a minimum elevation mask (Gougeon et al. 2001)).

Various studies investigating the integration of lidar and multispectral data have been undertaken. These studies generally illustrate that data acquisition parameters for both the imagery and laser data need to be customized for the purpose of integration. In addition, pre-processing to eliminate holes in the canopy without altering the ground hits at the edge of trees needs additional development. Furthermore, standard DEM generation techniques need improvement for this application and perhaps specialized methods developed that take into account the 3D shapes expected in a forest canopy. For instance, Leckie et al. (2003), have shown that with existing sensor and processing systems, a high density combined multispectral and lidar data set suitable for individual tree crown isolation and tree height measurement can be created. In this study, isolations were done using the orthorectified individual digital camera image frame resampled to 50 cm resolution, and the 25 cm Canopy Height Model was resampled to 50 cm and a 3x3 average filtering applied (). Data integration may also confer unique attributes. Lidar or multispectral data may be used to isolate individual trees. Each of these isolated tree objects may have a range of vertical or spectral attributes assigned. For instance, the mean spectral characteristics at differing vertical locations in a stand may be identified (). Refined mapping of species, including by strata, may be aided by such analyses (Coops et al. in review). When integrating lidar and multispectral data, the nature of the data types must be considered. Lidar, as an active senor, will consistently characterize an area, irregardless of illumination conditions (that can impact passive optical data).

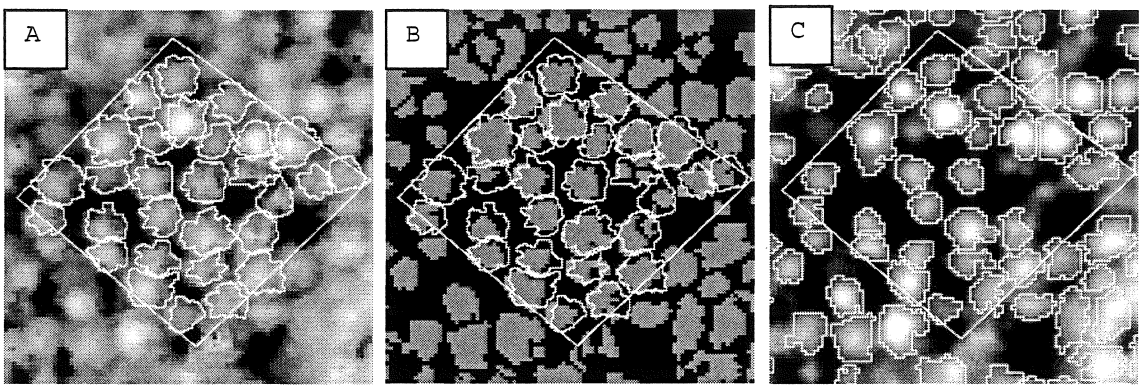

Figure 1 A. Ground referenced delineations in plot 18 over canopy height model (CHM) image resampled to 50 cm/pixel; B. Individual Tree Crowns or in bitmap format added to Figure 5A; C. Resulting automatically delineated individual tree objects (polygons) after the application of height and size filters (From Leckie et al. 2003).

An additional area of research in Canada pertains to the characterization of deciduous stands. While the majority of Canada's forests are conifer, some areas are dominated by deciduous and mixed conifer / deciduous stands. Lim et al. (2003b) have been exploring the use of lidar to characterize deciduous forests. The large overlapping crowns of deciduous stands have similarities to the broad leaf evergreen trees that are prevalent in Australia.

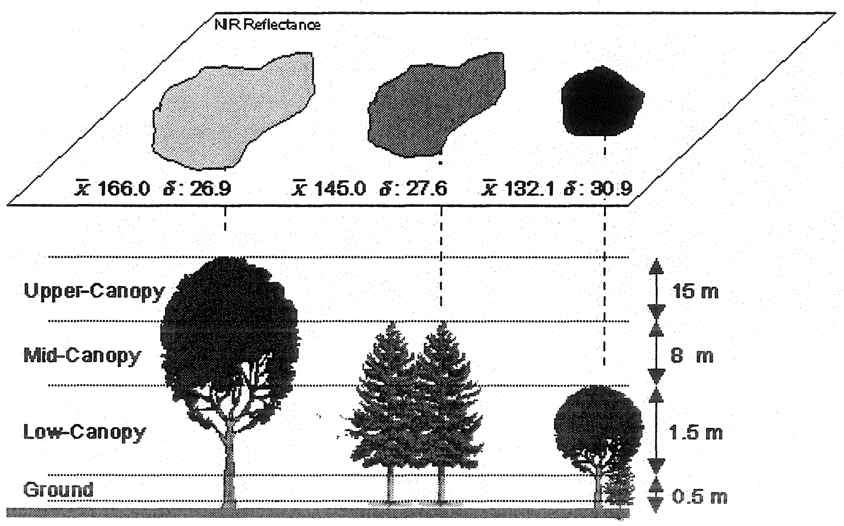

Figure 2. Mean near infrared digital number height classification based upon LIDAR height estimates (From Coops et al. 2003).

Biophysical

The use of lidar to characterize biophysical attributes is common with waveform recording lidar (Lefsky et al. 1999); the use of discrete return time of flight lidar to characterize forest structure is nascent in comparison. The use of small footprint lidar to characterize biomass is often based upon relationships between height and volume (then to biomass). With waveform-recording lidar forest canopy and stand structure is well documented (Lefsky et al. 2002). Biomass has been found to be non-asymptotic to 1200 mg/ha. Interest has been directed towards determination of how generalizable above ground biomass estimates are. Lefsky et al. (2001), compared above ground biomass in three biomes. The result of this research was a single robust biomass equation. The conclusion derived from this research is that indices of forest structure can be predicted from lidar generated canopy indices. Additional attributes that are estimated with lidar are LAI and gap fraction.

Gap fraction may be estimated at the stand or regional level. Regional level gap fraction estimates using large footprint waveform lidar may be used to calibrate models of LAI. Comparisons of fine (2m) and coarse (30m to 500m) spatial resolution estimates of leaf area index over BOREAS tower flux sites suggests that coarse resolution estimates typically overestimate LAI in stands with substantial clumping at crown and stand scales. A theoretical formulation for crown and stand scale clumping is developed based on existing approaches to estimating within stand clumping using in-situ gap fraction instruments. A stand scale-clumping index is estimated using SLICER data over BOREAS tower flux sites and applied to correct scaling errors coarse resolution LAI estimates (Fernandes et al. presentation).

Gap-fraction is usually determined by radiation instrumentation (e.g., hemispherical photographs, light-sensors) either at particular locations or along transects. While biomass estimates and gap-fraction are two essential pieces of forest structural information, they are usually incompatible with each other: the high density and fine spatial resolution of small footprint time of flight lidar estimates of gap fraction, lidar data makes it possible to derive top-of-canopy and gap-fraction as surfaces (Todd et al. 2003). Three-dimensional maps of foliage distribution were computed as stacks of the percentile probability surfaces (i.e., probability of a lidar pulse being returned from foliage at a given height within the canopy). These probability surfaces showed good correspondence with individual tree-based observations and provide a much more detailed characterization of quasi-continuous foliage distribution. These results suggest that discrete-return lidar provides a promising technology to capture variations of foliage characteristics in forests, providing functional linkages between biophysical and ecological studies.

Lidar in industrial forest management

Some operational foresters have identified the potential of lidar as a data collection tool in industrial forest management. The information generated from lidar is desired for assisting in harvest planning, and landscape level management. Industrial forest management agencies have existing inventory protocols based upon the interpretation of air photos and field checks.

The interest in lidar is also linked to increased user demand for high quality DEM for logging operations. Over many jurisdictions, new regulations require an efficient collection of forest inventory data, including for riparian buffer zone management. While the potential for lidar in operational forest management is clear. Operators often focus on the limits of lidar, which in their context include:

1. Cost of lidar data and processing.
    - If spending constant, what will not be collected?

2. Engineering versus inventory.
    - What organizational unit should pursue the lidar data?
    - Can internal co-ordination enable the collection of lidar for terrain and inventory purposes?

3. Need for commercial provision of lidar products.
    - Forest management agencies do not wish to employ lidar experts (already use contractors for many aspects of forest inventory generation)
    - Want consistent products.
    - Protocols can be built upon consistent products and pricing.

LIDAR IN REGIONAL CHARACTERIZATION THROUGH SAMPLING

As mentioned previously, both Canada and Australia (and the United States) have large areas of land that need to be characterized (at various levels of detail). To meet the objectives of large area characterization and high detail, lidar has been explored as a sampling tool. Lidar can provide for calibration and validation data for the characterization of larger areas. Field sampling in remote areas can be costly, making lidar a viable alternative. Additionally, as was previously mentioned, lidar can be used in conjunction with forest inventory data or satellite imagery. Lidar data provide accurate measurements of forest canopy structure in the vertical dimensions, yet current lidar sensors have limited coverage in the horizontal dimension. Existing and planned satellite missions are also envisioned to make sparse measurements in widely spaced transects. Landsat satellite data provide extensive coverage of generalized forest structural classes in the horizontal dimension but are generally insensitive to variations in forest canopy height. Forest inventory update cycles in Canada are often on the order of 10 years. The update of the forest inventory is often also done incrementally over a particular land base. As a result, lidar data can be used as a data source for the update of forest inventory maps. Estimates of stand height are an integral component of forest inventories. Lidar has been demonstrated as a tool for remotely sensing information on the vertical structure of forests, such as height. The ability to remotely sense height information for forest inventory purposes may allow for procedures such as up-date, audit, calibration, and validation (Wulder and Seemann 2003). The ability to use a regression model to spatially extend a lidar survey from a sample to a larger area would act to decrease costs while allowing for the characterisation of a larger area (Figure 3). Object based segmentation is used to partition the image into spectrally/ structurally similar units. Relationships are built between segments and co-registered lidar heights. The segment / lidar estimates of height generally form a range centred on zero (no difference) to +/- 6m of the ground measured height for over 80 % of the available validation plots, with a r^2 of 0.67 and a SE of 3.30 m. A reasonable SE, in locations such as this study area, where forest inventory heights are recorded in 5 m classes.

The extension of lidar estimates over image data may also be aided using spatial analysis procedures. Using an airborne discrete-return lidar system Hudak et al. (2002), tested five aspatial and spatial methods for predicting canopy height from Landsat ETM+ data. Integrated models that kriged or cokriged regression residuals were preferable to either the aspatial or spatial models alone, because they preserved the vegetation pattern like regression yet improved estimation accuracies above those predicted from the regression models alone. A 250 m point sampling strategy proved most optimal, as it over sampled the landscape relative to the geostatistical range of actual spatial variation as indicated by the sample semivariograms, while making the sample data volume more manageable. An integrated modeling strategy is most suitable for estimating and mapping canopy height at locations unsampled by lidar, and that a 250 m point sampling strategy would be more useful for lidar-Landsat ETM+ integration than sparser transect sampling strategies planned for satellite missions. The use of lidar data to calibrate Landsat-based forest structure maps has also been undertaken (Scarth et al. presentation). The lidar data was used to generate locationally specific inputs to a regional scale application of a geometrical optical model. The lidar data provided for stand level model calibration.

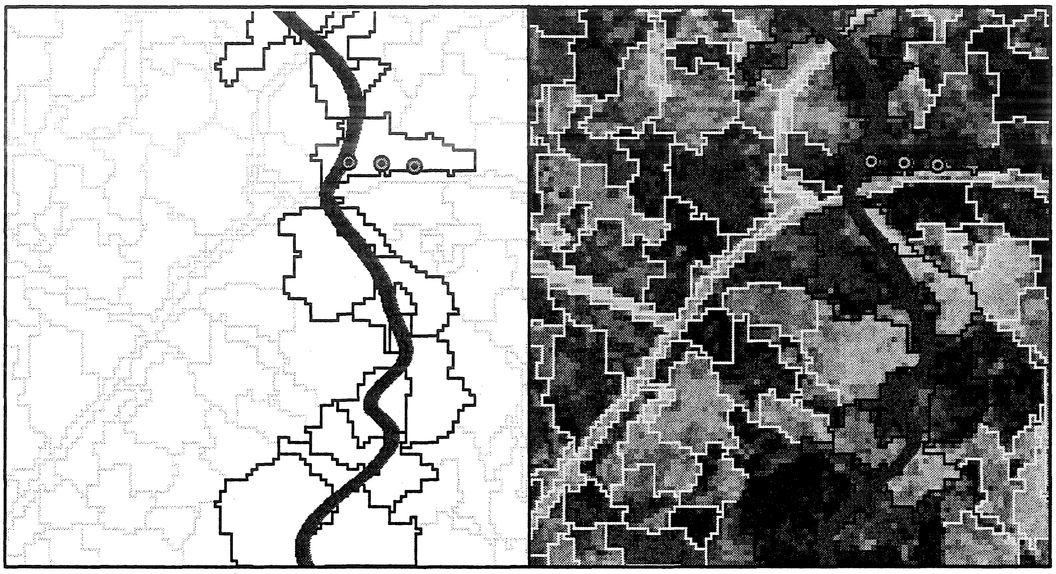

Figure 3. Illustration of segments with lidar data (dark blue), segments with no lidar data (light blue), a SLICER flight line (red), and some field plots (green/black circles). Both figures show the same segment information, but the right hand window has the Landsat-5 TM (G, R, IR) data as a backdrop to illustrate the segmentation results (From Wulder and Seemann 2003).

In Australia, various large area projects utilizing samples of lidar data have been undertaken, including the Bureau of Rural Sciences (Lee presentation) and the Queensland Department of Natural Resources and Mines (Weller et al. 2003). As an example, a multi-agency consortium including Raytheon, multiple layers of government, and universities, used airborne scanning lidar and large scale photography for providing stand-based and local to regional estimates of woodland biomass and structure near Injune, Queensland, Australia. The study focused on a 60 x 40 km (220,000 km^2) area of woodland. Estimates of vegetation height, tree density, structural attributes and biomass were derived using lidar. This study demonstrated the advantages and cost-effectiveness of using large scale photography for land and forest assessment, and identified significant improvements that can be made using lidar technology. This work also demonstrated the potential of using airborne lidar for operational monitoring of the structure and biomass of Australia's diverse multi-aged forests and woodlands more accurately and cost-effectively than traditional field surveys alone (Tickle et al. presentation).

WORKSHOP RECOMMENDATIONS AND GENERAL CONCLUSIONS

Gathering government, university, and industry participants to the lidar workshops was of great benefit. The range of participants ensures that there is a link between the research undertaken and needs of industry. A variety of recommendations and observations can be made regarding the workshops and the general state of lidar remote sensing of forests and terrain in Canada and Australia. The forest management industry voiced interest in the pursuit of demonstration case studies in areas where there are established applications, and also development of standard products, definitions, and algorithms. Ultimately, the forest management industry wants to know that lidar products will be delivered to consistent standards and costs. The cost effectiveness of lidar emerges as a concern of the forest industry, resulting in an interest in a clear cost-benefit analysis comparing lidar to standard operations. Consortiums have been developed as a pragmatic means to alleviate costs to an individual organization. From the value-added lidar processing community, there is interest in the development of a user-friendly toolbox of lidar algorithms, developed to generate information on a range of attributes, including robust terrain and canopy height models. The current suite of attributes that may be discerned with the aid of lidar data are useful information inputs to traditional forest management. Development of new algorithms that take advantage of the lidar information content are also desired. New algorithms may improve the characterization of forest structure, habitat, and forest health. Additional advances in data integration between lidar and other remotely sensed and spatial data sources will further efforts in this regard. Effort invested in researching and developing applications for lidar as a sampling tool for characterizing large areas is appropriate to Australian and Canadian geographic and political conditions.

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INVENTORY AND MONITORING OF FOREST RESOURCES WITH SMALL FOOTPRINT LIDAR: AN OVERVIEW OF CURRENT ACTIVITY AND NEAR-TERM TRENDS

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ABSTRACT

Small-footprint imaging lidar systems now dominate much of forest remote sensing research and development and are being gradually integrated into operational inventory and monitoring. This keynote address will highlight developments in both sensors and algorithms with a focus on recent North American activity in both areas. In addition to this technical overview, results of a survey of large (> 400,000 ha) forest landowners will be presented to highlight institutional informational needs and what lidar data and applications are best suited to fulfill these requirements.

LASER SCANNING OF FOREST RESOURCES – THE NORWEGIAN EXPERIENCE

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ABSTRACT

The status of research and application of airborne laser scanning in forestry in Norway is presented. Results from previous trials are discussed, and the main focus is on methods for large-scale practical inventory of forest resources for forest planning and management. Ongoing research activities are also presented. Finally, some ideas about the direction of future research and application development are discussed.

INTRODUCTION

The history of laser scanning of forest in Norway goes back to 1995. Two small pilot studies (Næsset 1997a, b) indicated that laser scanning could be an interesting method for derivation of important biophysical properties of forest trees and forest stands estimated in conventional forest inventories and used in forest planning and management. The last decades, much of the research activities at the Department of Forest Sciences have dealt with improvement of inventory procedures, planning procedures, and tools and models for long-term analysis of management practices at forest stand and property level. It has therefore been quite natural that the laser research has focused on practical methods for inventory of forest stands and forest properties. Forestry is a small sector in Norway with very limited impact on the national economy. There are also small budgets for forest research in general. One consequence has been that practical forestry and public research have joined their limited resources in finding inventory methods for practical use. The development of laser-based techniques has partly been accomplished to meet the requirements from the forest sector, including private companies. Thus, most trials conducted so far have dealt with practical aspects of applying laser scanner data to collect stand-wise characteristics for forest planning purposes.

This article presents the current status of laser research in Norway. It gives a brief overview of the experiments that have been carried out and the main results are presented. Current research activities and future prospects are also discussed.

TWO INITIAL STUDIES

The first experiments were carried out in 1995 in 36 coniferous stands in the eastern part of Norway. The main objectives were to derive mean tree height (Næsset 1997a) and stand volume (Næsset 1997b) of individual stands based on laser scanner data with an average spacing of 2.8-3.3 m. The flying altitude was 640-825 m and the average footprint diameter was around 13-16 cm. Maximum scan angle (off nadir) was 20 degrees (Table 1). Dominant tree species were Scots pine in the first test site and Norway spruce in the second one.

Table 1: Summary of field data and laser scanner data of sampled forest stands in the two initial studies (Næsset 1997a, b).

Test site	No. of Stands	Mean stand size (ha)	G (m^2ha^{-1})	h_L (m)	V (m^3ha^{-1})	Mean no. of transmitted pulses per stand		Scan angle (deg)
						Total	Vegetation hits	
1	18	1.5	12.6-53.8	8.1-24.3	49-472	1350	505	0.8-19.2
2	18	1.5	12.6-35.3	8.2-20.1	53-283	1910	1070	0.9-14.3

G=basal area; h_L=Lorey's mean height; V=stand volume.

First, mean tree height of the test stands were compared with the average value of all laser pulses that were classified as canopy hits. It was revealed that the mean value computed from the laser data seriously underestimated the ground truth by 4.1-5.5 m (Table 2). A similar tendency of underestimation has been reported in many other studies. There are two major reasons for this underestimation; (1) with a scattered sample of the laser pulses (large spacing) the probability of hitting the tree apex is small. A large portion of the pulses will therefore be reflected from the lower part of the tree crowns, and (2) the light transmitted by the laser will usually penetrate the outer surface of the tree crowns before a significant return signal is recorded. However, as the laser sampling intensity increases the bias will tend to decrease.

To eliminate the impact of laser pulses that are reflected from the lower parts of the canopy, a grid-based approach was considered. The stands were divided into regular grid cells of equal size and only the maximum laser height value within each cell was retained. The laser mean height of a stand was computed as the arithmetic mean of these cell maxima. Such computations were carried out for different cell sizes. For cells with size 15X15 m the laser-based mean height estimates were unbiased and the precision was fairly high (1.2-1.3 m, Table 2).

The grid-based approach was tested for estimation of stand volume as well. Regression analysis was used to estimate volume equations applying multiplicative models with grid-based mean height (15 m grid cells) and canopy density as derived from the laser data as independent variables, i.e.

$$V = \beta_0 h_{15}^{\beta_1} D^{\beta_2} \quad (1)$$

where V=stand volume, h_{15}=laser mean height based on 15 m grid cells, and D=canopy density. D was computed as a mean value of each stand of the number of canopy hits divided by total number of transmitted laser pulses within each grid cell.

The results of the regression analysis indicated that a large portion of the variability in stand volume was explained in the spruce forest (test site 2). The R^2 value was 0.84 (Table 2). In the pine forest, the R^2 value was low (0.47).

Table 2: Comparison of ground-truth mean height (h_L) with different mean height estimates derived from laser data (Næsset 1997a), and results of analysis of stand volume regressed against mean height and canopy density as derived from laser data according to Eq. 1 (Næsset 1997b).

Test	h_m-h_L		h_{15}-h_L		h_{20}-h_L		h_{30}-h_L		*Volume regression analysis*	
site	Bias (m)	SD (m)	Bias(m)	SD (m)	Bias (m)	SD (m)	Bias (m)	SD (m)	R^2	CV (%)
1	-4.1	1.6	-0.4	1.3	0.3	1.3	1.1	1.3	0.47	42.7
2	-5.5	1.3	0.1	1.2	0.9	1.2	1.9	1.3	0.84	20.9

h_L=Lorey's mean height; h_m=mean laser height value of all canopy hits; h_{15}=mean laser height based on 15 m grid cells; h_{20}=mean laser height based on 20 m grid cells; h_{30}=mean laser height based on 30 m grid cells.

The conclusions of these two initial studies were that (1) by dividing forest stands into regular grid cells and extracting maximum laser height values within each cell, it was possible to obtain very precise estimates of stand height, and (2) by combining laser height metrics and vegetation density metrics derived from laser data of grid cells, it was possible to estimate stand volume by regression analysis.

REQUIREMENTS FOR PRACTICAL FOREST INVENTORY PROCEDURES

The two initial trials lead to the idea that it might be possible to inventory large forest areas by airborne laser provided that precisely geo-referenced field sample plots could, in a first phase, be used to develop empirical relationships between laser scanner data and the stand characteristics of interest, such as mean tree height, dominant height, mean diameter, basal area, stand volume, stem number, and, in a second stage, such relationships could be used to predict corresponding characteristics of entire forest stands. However, a critical part of this procedure was the georeferencing of field plots below tree canopies. Current status of research around 1996-1997 indicated a potential accuracy of differential GPS measurements under tree canopies of 3-4 m (Deckert and Bolstad 1996). This accuracy was considered to be inappropriate for precise measurements of small sample plots in boreal forest since errors of this magnitude will introduce a large variability in relationships between laser data and ground data due to spatial heterogeneity (Bolduc *et al.* 1999). Efforts were therefore made to find appropriate GPS equipment, and GPS measurement and processing procedures that could meet the requirements for high-precision field inventory. In the period 1997-1999, we tested several types of GPS and GLONASS receivers and different measurement and processing procedures to obtain the requested level of precision (<0.1-0.5 m under tree canopies). Tests have indicated an average positional accuracy of 0.2-0.7 m under tree canopies with basal area up to about 40 m^2ha^{-1} using combined GPS+GLONASS dual-frequency measurements and observation periods around 15-20 min. In the following laser research, we have applied the very best of these procedures and carefully selected the best equipment (Næsset 1999, 2001; Næsset *et al.* 2000; Næsset and Jonmeister 2002). Practical use of these procedures in later laser trials has indicated an average positional accuracy of field sample plots of 0.2-0.3m (Næsset 2002a, 2003).

PRACTICAL LARGE-SCALE FOREST INVENTORY

The two-stage procedure for stand inventory of large forest areas based on laser data in which stand estimates of biophysical properties were computed by regression equations developed from field plots were first described by Næsset and Bjerknes (2001). The first validation of the proposed inventory procedure was accomplished in a 10 km^2 study area in 1999 covered with laser data with an average spacing of about 0.9 m (Næsset 2002a). In this validation, 144 sample plots of size 200 m^2 were distributed systematically throughout the 10 km^2 study area. The plots comprised young and mature forest, and dominant species were Norway spruce, Scots pine, and birch. The plots were divided into three strata according to age and site quality: (1) young forest, (2) mature forest with poor site quality, and (3) mature forest with good site quality.

For each sample plot, canopy height distributions were derived from first and last return laser data. Canopy densities were also computed from the first and last return laser data. These densities were computed for different fractions of the height distributions. A total of 20 canopy density variables were derived for each plot. Thus, more than 40 potential laser-derived variables were available for further analysis. Regression analysis with stepwise variable selection was used to derive regression models for the stand characteristics of interest, i.e. mean tree height, dominant height, mean diameter, basal area, stand volume, and stem number. Multiplicative models were applied and they were estimated in logarithmic form. For mean height and stand volume the models explained 82-95% and 80-93% of the variability, respectively (Table 3).

Table 3: Relationships (R^2) between logarithmic transformations of ground-based characteristics of 200 m^2 sample plots (dependent variables) and laser-derived metrics from stepwise multiple regression analysis (Næsset 2002a).

	Dependent variable					
Stratum	h_L	h_{dom}	d_g	N	G	V
Young forest (*n*=56)	0.95	0.93	0.78	0.68	0.89	0.93
Mature forest, poor site quality (*n*=36)	0.86	0.74	0.54	0.65	0.69	0.80
Mature forest, good site quality (*n*=52)	0.82	0.85	0.39	0.50	0.75	0.80

h_L=Lorey's mean height; h_{dom}=dominant height; d_g=mean diameter by basal area; N=stem number; G=basal area; V=stand volume.

The estimated regression equations were used to predict corresponding biophysical properties for all forest stands in the given strata over the entire 10 km^2 study area. The grid-based approach was used, i.e. the study area was divided into regular grid cells with cell size equal to the sample plot size (200 m^2). Mean values of the predicted characteristics were computed for each forest stand as the arithmetic mean of the individual grid cell values. A total of 61 stands were selected as test stands to validate the accuracy of the proposed practical procedure. The stand area ranged from 0.7 ha 11.7 ha. A field inventory of the 61 stands was accomplished to obtain ground-truth data. The stands were divided into three strata according to the criteria used for the sample plots.

The testing indicated high precision and small bias for most of the validated characteristics (Table 4). For mean height, the precision was 0.61-1.17 m and the bias ranged from 0.01 m to 0.42 m. For stand volume, the precision was 18.3-31.9 m^3ha^{-1} (11.4-14.2 %) and the bias was 0.3-8.2 m^3ha^{-1}.

Table 4: Mean difference (bias) between predicted and ground-truth values of six investigated bio-physical stand properties, and standard deviation (SD) for the differences in stand predictions using regression equations derived from independent sample plots (Næsset 2002a).

Variable	Ground-truth mean	Bias	SD
Young forest (n=22)			
h_L (m)	13.90	0.42*	0.87
h_{dom} (m)	16.62	-0.08ns	1.33
d_g (cm)	13.23	0.72*	1.60
N (ha^{-1})	1844	-90ns	400
G (m^2ha^{-1})	23.79	-0.86ns	2.48
V (m^3ha^{-1})	168.0	6.2ns	24.0
Mature forest, poor site quality (n=19)			
h_L (m)	16.37	-0.09ns	0.61
h_{dom} (m)	18.07	-0.31ns	0.70
d_g (cm)	21.17	0.78*	1.61
N (ha^{-1})	577	15ns	128
G (m^2ha^{-1})	19.84	0.74ns	2.33
V (m^3ha^{-1})	154.8	8.2ns	18.3
Mature forest, good site quality (n=20)			
h_L (m)	19.77	-0.01ns	1.17
h_{dom} (m)	22.38	-0.43ns	1.32
d_g (cm)	21.24	0.98**	1.37
N (ha^{-1})	856	-103**	145
G (m^2ha^{-1})	29.66	-0.67ns	2.54
V (m^3ha^{-1})	280.5	0.3ns	31.9

h_L=Lorey's mean height; h_{dom}=dominant height; d_g=mean diameter by basal area; N=stem number; G=basal area; V=stand volume. Level of significance: ns=not significant (>0.05). * <0.05. ** <0.01.

In 2001, a second test of the proposed procedure was carried out in a 65 km^2 study area. The dominant tree species were Norway spruce and Scots pine, but at several sites the stands were dominated by deciduous species. The terrain was hilly with steep slopes and the flying altitude varied considerable within the area. A small-footprint scanning laser was used, and on the average the distance between transmitted pulses was 1.0 m on the ground. A total of 116 sample plots with size 233 m^2 were distributed systematically throughout the entire study area, and they were divided into the three strata defined in the first study (see above). These sample plots were used to develop regression equations with ground-based values of the six stand characteristics mentioned above. The selected regression models explained 60-97% of the variability, and in general their properties were quite similar to those reported in the first study. Predictions were made for 57 large control plots with a size of about 0.4 ha each. These plots were selected independent of the 116 small sample plots. The predictions yielded results that were similar to those obtained in the first study. Precision for mean height ranged from 0.64 m to 1.01 m and for volume from 15.1 m^3ha^{-1} to 35.1 m^3ha^{-1} (9.3-12.2 %) (Næsset 2002b, 2003).

It was revealed that large variability in flying altitudes and laser sampling density had little effect on the precision of the validated procedure. However, mixture of coniferous and deciduous species may degrade the precision seriously. Regression equations developed from a material of coniferous sample plots will also tend to provide biased estimates of stands with a large portion of deciduous trees.

The main conclusions from these trials are that the proposed procedure seem to be robust for use in practical inventories over large areas, at least if the forest is dominated by coniferous species.

Topographic variability and variability in laser sampling density seem to have little impact on the applicability of the procedure. The bias seems to be at an acceptable level, and the precision for the evaluated stand characteristics is higher than for all competing inventory methods. The method is also superior to conventional inventory methods as far as inventory costs and data utility in economical terms are concerned (Eid *et al.* 2003). The laser-based procedure was introduced as a commercial inventory method in the Norwegian market in 2002 and the two first inventories are carried out in 2003.

Further research in this field should focus on methods to deal with the problems that arise in mixed forest. One option could be to treat deciduous stands and mixed stands as separate strata, but such stand types usually cover only a small portion of a survey area in boreal forest. Collection of laser data under off-leave conditions could be another option. In spite of the rapid technological development and falling prices for laser data acquisition, laser data collection still accounts for a large portion of the total inventory costs. Analysis has been accomplished to find a reasonable trade-off between sampling density of the laser data and the accuracy of the inventoried properties. This research activity should continue.

Reducing the field effort of laser-based methods is a second opportunity to reduce inventory costs. Several scientists have proposed model-based approaches to inventory trees and forest stands without using field data for model derivation. However, the costs of the field-phase could be reduced even for empirically based methods that rely on field data. In the two trials carried out so far, sample plots have been collected locally for each trial. It should be considered carefully whether local plots are needed. In regions where the climatic conditions are similar and the trees tend to develop similar stem and crown shapes, it might be possible to take advantage of sample plots from adjacent survey areas. Thus, a data-base of previously inventoried sample plots with corresponding laser data could be a valuable asset for future inventories. Preliminary analysis indicates that this could be a technical and economical sound strategy, but more extensive research under different forest conditions is required.

INVENTORY OF YOUNG REGENERATIONS

The outlined procedure aims to provide forest stand data complying with the data requirements of forest planning and management in young (tree heights >8-10 m) and mature forest. In young regenerations (tree heights <8-10 m), the data requirements are normally less extensive than in the mature forest. However, it has been an aim that airborne lasers should provide much of the data basis needed for forest management in all stages of stand development in boreal forest. In the youngest stands, stem number and tree height are important biophysical characteristics. Attempts have therefore been made to derive these properties.

In 1999, a field work was carried out for 39 sample plots with size 200 m^2 (Næsset and Bjerknes 2001). Trees taller than 1.5 m were counted and the heights were measured on sample trees selected according to a sampling scheme that resulted in dominant height estimates. Dominant height ranged from 1.8 m to 6.0 m with an average value of 3.8 m. Stem number ranged from 1650 ha^{-1} to 7100 ha^{-1}. Laser scanner data with an approximate spacing of 0.9 m were acquired. Regression analysis revealed that various measures of canopy height and canopy density derived from the laser data could explain approximately 80% and 40% of the variability in ground-measured mean height and stem number, respectively (Næsset and Bjerknes 2001).

We also tested the outlined inventory procedure in young regenerations. A total of 12 young forest stands with a mean height of 6.6 m was measured in field, and regressions developed from the 36 sample plots were use to predict stand heights by the grid-based approach. The bias of the predictions was 0.2 m ($p>0.05$) and the precision was 0.56 m (Næsset and Bjerknes 2001). These results have been confirmed by corresponding findings from another and more extensive trial not published so far.

In the boreal forest, natural regeneration regimes are important parts of the silvicultural practice. In Scandinavia, natural regeneration is typically applied to Scots pine, at least on sites with medium to low productivity. Since seed trees may remain in the future stands for many years after the regeneration has been ensured, utilisation of laser data for such sites may be difficult unless prior information about the stand is available. Given that updated information about the presence of seed trees is provided, preliminary analysis indicates that airborne laser could be an efficient data source for estimation of properties of the regeneration as well as of the dominant seed trees. Furthermore, analysis indicates that relevant characteristics of the seed trees that may be derived from laser data comprise individual tree heights as well as tree positions, even when the laser sampling density is less than 1 pulse per m^2. Further research is required to present a complete package of tools for practical inventory of young forest from laser data.

OTHER BIOPHYSICAL PROPERTIES

Traditionally, forest inventory has been concerned with providing data for an efficient timber production. Consequently, properties of interest have been those that quantify the standing timber volume and the capacity for future wood production. An interesting "family" of biophysical properties of trees and forest stands that have received increasing attention over the last years, are properties related to the tree canopy and the tree crowns. These properties are probably of importance for understanding of the forest ecosystem functioning as such (Lefsky *et al.* 2002), but they may also be useful for description of solid wood quality (Næsset and Økland 2002). Laser data are very suitable for tree canopy modelling.

Many studies dealing with identification and modelling of individual tree crowns have been published recently (e.g. Persson *et al.* 2002; Brandtberg *et al.* 2003). However, most of these studies have indicated that a large sampling intensity, say >3-5 pulses per m^2, is required to characterise the properties of individual trees. Because properties such as height from the ground to the living crown and crown length may be used as indicators of solid wood quality in forest inventories, we analysed the ability to determine these characteristics of individual trees and for the average of several trees within plots from small-footprint laser data with moderate spacing. In 1999, laser data with an average spacing of 0.66-1.29 m were acquired over two different sites in eastern Norway (Næsset and Økland 2002). One of the sites was a boreal nature reserve. The other one was a private forest property managed according to ordinary silvicultural practice. Both sites were dominated by Norway spruce and only mature forest was included in the trial. In the first study, tree crown projections and tree heights and crown heights of all trees within 10 plots with size 50 m^2 each were recorded. Mean height ranged from 14.1 m to 25.4 m. In the second study, 27 sample plots with an area of 200 m^2 were inventoried in field. Tree height and crown height were measured for all trees with d_{bh} >15 cm.

Canopy height distributions and corresponding canopy densities were derived from the first and last return laser data and regression analysis was used to relate the field-measured crown properties to the laser data. In the first study, height distributions were derived for individual crowns as well as for entire plots (50 m^2). In the second study, height distributions were derived at the plot level (200 m^2). The regression models were validated by cross-validation. Two different crown properties were assessed, i.e., the height from the forest floor to the living crown (h_c) and the relative crown height (R_c). Relative crown height was defined as the crown length as a percentage of total tree height.

Table 5: Mean difference (bias) between predicted and ground-truth values of height to the crown and relative crown length of individual trees and sample plots, and standard deviation (SD) for the differences in cross-validation of regression equations derived from laser data (Næsset and Økland 2002).

Variable	No. of observations	Ground-truth mean	Bias	SD
Study 1 (boreal nature reserve)				
$h_{c(t)}$ (m)	45	5.60	0.03ns	2.19
$R_{c(t)}$ (%)	45	70.44	0.16ns	10.48
$h_{c(p)}$ (m)	10	5.31	0.01ns	1.24
$R_{c(p)}$ (%)	10	71.51	0.17ns	6.32
Study 2				
$h_{c(p)}$ (m)	27	7.28	0.05ns	1.52
$R_{c(p)}$ (%)	27	65.25	0.05ns	7.11

$h_{c(t)}$=height to the crown for individual trees; $h_{c(p)}$=average height to the crown for trees within plots; $R_{c(t)}$=relative crown length for individual trees; $R_{c(p)}$=average relative crown length for trees within plots. Level of significance: ns=not significant (>0.05).

The validation revealed large standard deviations for the differences between predicted and observed h_c of individual trees as well as for the average of all trees within plots. For individual trees, the standard deviation was 2.19 m (Table 5), which is 39% of the ground-truth mean value (Næsset and Økland 2002). At plot level, the standard deviations ranged from 1.24 m to 1.52 m (21-23%). The relative crown height was predicted with higher precision. For individual trees, the standard deviation was 10.48%, which is 14.9% of the ground-truth mean value. At plot level, the precision was 6.32-7.11% (8.8-10.9% of the ground-truth mean).

This trial, though limited in the total number of observations, may indicate that certain crown parameters can be derived from laser data with moderate sampling density. Industrial actors are now evaluating the value of crown parameters as means for timber quality assessment in wood procurement. Continued research is required to further develop and take advantage of crown parameters derived from laser data as wood quality indicators for different tree species.

FUTURE RESEARCH

Based on the experience gained in Norway so far, there seem to be at least three main directions of future research on airborne laser in forest applications that we will focus on in the near future. These major directions are (1) improvements and extension of the practical inventory procedure outlined above based on laser data with moderate sampling density, (2) further development, testing, and implementation of procedures for detection and measurement of characteristics of individual trees by laser data with high sampling density, and (3) extension of research and application development to new fields of importance to forest- and ecosystem management and certification, such as biodiversity assessment.

Actions taken by the actors in the market of forest inventory services seem to indicate that laser scanning of forests with moderate sampling density has become an interesting alternative to current inventory procedures from a commercial point of view. As long as the data requirement for forest management is restricted to mean values at stand level (mean height, mean diameter, mean volume, etc), the proposed inventory procedure seem to comply with the needs in forest management. However, many of the management planning tools and packages developed for Nordic users utilize models requiring more detailed stand information, such as for example growth models for individual trees. For the most extensive planning packages, tree-level data would be needed. However, in many packages the stand diameter distribution is the linkage between advanced tree-level models and the characteristics that are actually captured in practical inventories. Since the canopy height distribution as derived from laser data of a certain area is likely to be highly correlated with the tree height distribution, it is likely that diameter distributions could be derived directly from laser data. We regard methods for derivation of diameter distributions from laser data as an important issue for future research, and preliminary work indicates that such distributions could be predicted from laser data with a precision superior to that of conventional methods (Gobakken and Næsset 2003). It is also important to do further assessments of how factors such as variable flying altitude and sampling density affect the accuracy of the biophysical properties derived from the laser data since these factors must be expected to vary considerably in large inventories covering up to 1000 km^2 or even more.

Although single-tree data would fulfill the requirements for forest management with the most sophisticated tools, the high laser sampling density that would be needed seem to be too costly at present. Nevertheless, as the capacity of airborne lasers continues to increase, the costs are expected to decrease. Even from a practical point of view, it is therefore important with a continued research within the field of single-tree segmentation based on laser data and combined use of laser data and image data. However, many of the studies accomplished within this field so far, have dealt with relatively simple conditions, such as even-aged forest, single species, and sites with regular tree spacing. The research within this field should be able to provide methods and algorithms to handle mixtures of tree sizes, species and irregular spacing to meet the requirements for practical applications.

Forest biodiversity is affected by factors that operate at a wide range of spatial and temporal scales. Many of the most significant processes in a forest ecosystem are related to the structure of the tree canopy. Organisms living in forests are strongly affected by the forest canopy, and the distribution and abundance of a wide range of species of plants and animals are related to the 3-

dimensional characteristics of the canopy. Since airborne lasers can capture the canopy structure in a forest and can provide data from large areas, laser scanning offers an exiting opportunity to extrapolate from detailed studies on the role of tree canopies in ecosystem processes to large scales which are more relevant for decision- and policy making at the ownership, landscape, regional or even national levels. Research on the relationships between canopy structure as derived from lasers and biodiversity will therefore be given priority.

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LASER SCANNING OF FOREST RESOURCES – THE SWEDISH EXPERIENCE

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ABSTRACT

An overview of the first 15 years of research in Sweden about laser scanning for assessment of forest resources is given. The authors come from the four organizations that until now have been most actively involved in this development in Sweden. The Swedish Defense Research Agency (FOI, previously FOA) pioneered the system development of laser scanners with the FLASH system and has also carried out research in data analysis. The early system development at FOI resulted in the two commercial systems HawkEye and TopEye, developed by SAAB. Recently the TopEye system has been operated by a separate company, TopEye AB. Researchers at the the Swedish University of Agricultural Sciences (SLU) in Umeå have worked with analysis of laser data of forests since 1989, first using profiling lasers, then the FLASH system in 1991, and the TopEye system from 1997 and onwards. Both the stand level and the single tree level have been addressed. Parts of the single tree research have been done in co-operation between SLU and FOI. FOI is also developing methods for integrating laser data and optical images on the single tree level, and for analysis of terrestrial scanner data. Methods for retrieving forest information, including analysis of single trees, from TopEye laser data have also been developed at the Centre for Image Analysis in Uppsala. Methods for retrieving stem volume information on stand level can now be considered near operational, and the first semi operational laser scanner flight for forest inventory purposes in Sweden were carried out in May 2003.

INTRODUCTION

The aim of this paper is to give an overview of the first 15 years of research, testing, and system development related to laser scanning of forest resources in Sweden. The most important laser flight missions in Sweden that are related to this field are listed in Appendix 1.

THE FLASH SYSTEM

During the mid 1980's a laser scanning system called FLASH was developed primarily for naval applications by the Swedish Defence Research Agency, FOI (at that time FOA), (Steinvall 1993, 1996, 1999). The FLASH system was a helicopter borne lidar bathymeter with key functions for real time depth imaging and programmable scanning (Axelsson et al., 1990). A short description of the FLASH system is given in Table 1. For a more detailed description of the system, we refer to the above references. The FLASH system was used for tests for Naval applications, and also for terrain mapping, It was then developed further by the SAAB company into two operational versions, under the name of Hawk Eye (Figures 1, and 2).

Table 1. FLASH system parameters

Laser: - Nd: YAG, 1.064 and 0,532 μm - Prf 200 Hz, Pulse energy 3-5 mJ **"Green" receiver:** - PMT, 20 cm telescope, filter 1,2 nm - FOV outer 5-50 mrad, inner blocking 0-10 m rad **"IR" receiver:** - Coax with green av photo diode - Land / water discriminator **Rec. Electronics:** - Log. Amplifier: 80 dB - LeCroy digitizer: 2,5 ns sampling at 8 bits - Constant fraction discr. for slant range - Slant range resolution 8 cm - Real time echo extraction	**Scanner:** - Programmable, semicircular scan pattern at 20° angle of inc. in normal mode - Hovering mode: ± 20° on y (⊥ nose dir.) + 35° / -5° (in nose dir.) **Storage:** - Ancillary data: Sensor parameters, navigational data - Full waveform every 6 th wave form at 200 Hz, all wave forms at 62 Hz - Video recorder **Navigation:** - Motorola mini ranger later replaced by GPS **Presentation:** - Waveform, depth coded colour display.

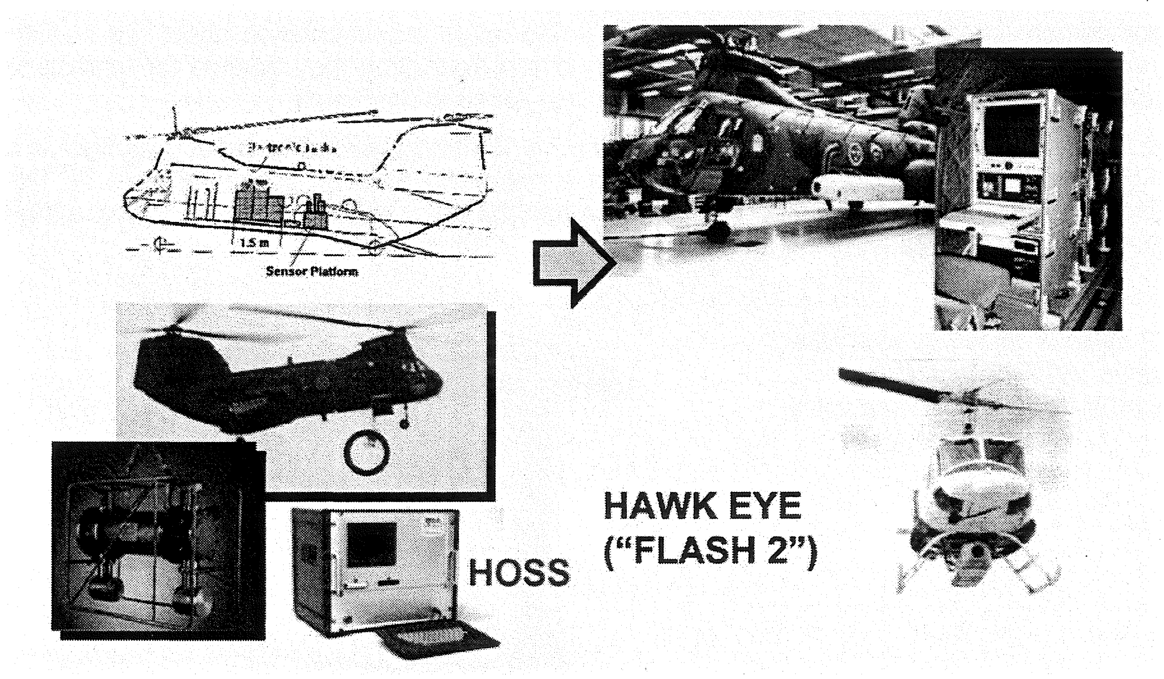

Figure 1. Left, the FLASH system installed in a Vertol helicopter plus an instrument called HOSS for measuring optical water parameters. Lower right image: the Pod mounted Hawk Eye system.

The differences between FLASH and Hawk Eye included: pod mounted transceiver system; better wave form sampling (10 bits, 1 ns); storage of every wave form; better signal handling, especially for echo extraction; better scanner accuracy; inertial reference system and GPS; more compact and easy installation; built-in planning and mission software; one shallow and one deep green channel; and PMT replaced by APD for deep green channel (later back to PMT again).

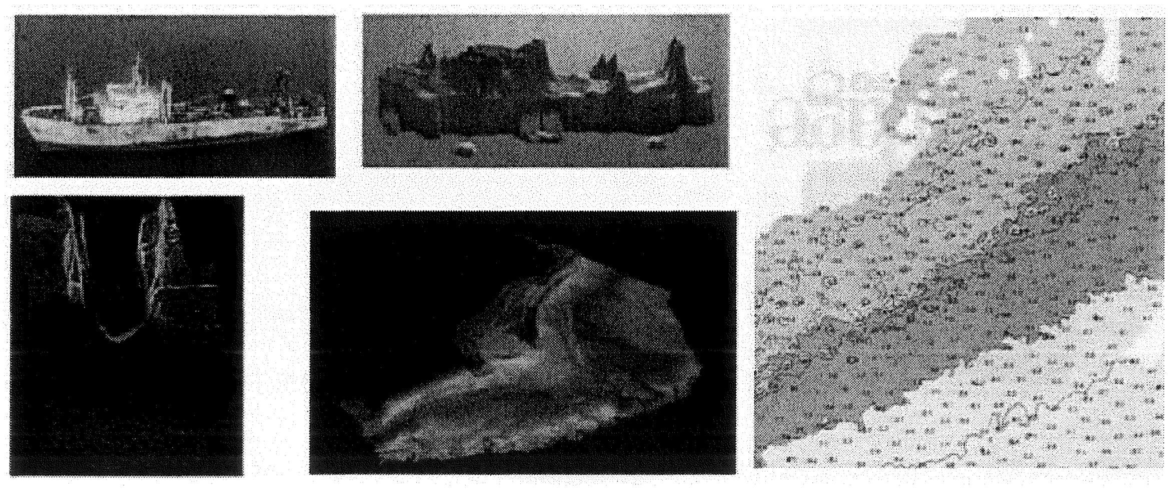

Figure 2. Type of depth sounding data products obtained from Hawk Eye. Above a 3-D image of the ship shown on the image top left, but lying at 26 meters depth in the Baltic and a colour coded depth 3-D presentations of the chart to the right.

EARLY STUDIES BY SLU IN UMEÅ

The forest remote sensing researchers at SLU in Umeå heard a presentation about the FLASH system at a FOA conference 1988. Encouraged by this presentation they applied for funding to investigate the potential of the laser scanning technology for forest inventory.

The first laser study at SLU in Umeå was carried out in 1989 by registering canopy profiles in a young Scots pine stand using a profiling laser from a crane mounted on a truck (Figure 3). The results indicated that both the standing stem volume and the stem volume removed during a thinning cutting could be estimated using laser height profiles (Nilsson, 1994).

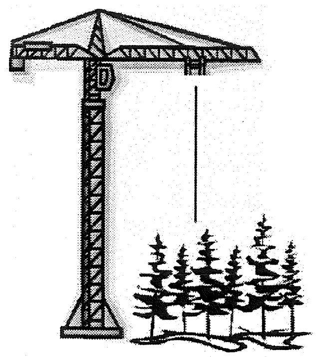

Figure 3. Sketch showing how canopy profiles were collected in 1989 using a profiling lidar mounted on a crane.

During 1991, three tests with a scanning laser were done in a coastal Scots pine stand. The project was carried out by SLU in co-operation with FOA using the FLASH system. The possibility to estimate tree height and stem volumes using distance measuring scanning laser systems was tested on plots with 10 m radius. The results showed that tree heights were underestimated by 2.1-3.7 m. It was also found that the waveform area (Figure 4) could be used in combination with laser measured tree heights to estimate stem volume. A regression model predicting stem volume using the mean product of the waveform area and the laser measured tree height as independent variable was derived (R^2 = 0.78). This work, which is reported by Nilsson (1996) is to our knowledge one of the first scientific articles where scanning lasers have been used for assessment of forest resources.

In his thesis, Nilsson (1997) also made a simulation study that showed that laser measured canopy height measurements would be a valuable complement to optical satellite data when estimating stem volume. He found that the RMSE for stem volume on a plot level decreased from 56 m^3/ha using TM data alone to 37 m^3/ha using a combination of TM data and field measured tree height data. If tree heights derived from airborne lidar data are used, the increase in accuracy will be lower. It was also evident that the overestimation of low stem volumes and the underestimation of high stem volumes were much less, when both TM data and tree height data were used, compared to TM data only.

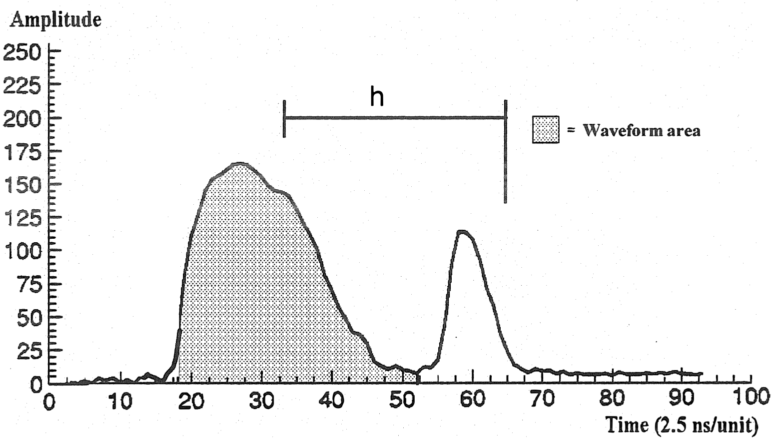

Figure 4. An example of a laser return (waveform). The figure also illustrates how the tree height (h) and the waveform area were defined (from Nilsson, 1996).

THE TOPEYE SYSTEM

A commercial laser system for terrestrial applications called TopEye was developed by SAAB in 1993 with the first flights made in 1995. The TopEye system is based on the same basic principles that where developed for the FLASH and HawkEye systems. The mechanical structure and electronics was significantly redesigned to be lighter and adopted to the data rate. The TopEye system is working with a pulse rate of 7000 Hz, the beam divergence is adjustable from 1- 8 mrad, both first and last return in an emitted pulse as well as the amplitude for the return can be recorded, see Table 2 for further system parameters.

Table 2. TopEye system parameters

Laser:	**Storage:**
- Nd: YAG, 1.064	- Tape and removable hard disk drives
- Prf 7000 Hz, Pulse length 4-7 ns	**Navigation:**
Receiver:	- GPS – Trimble 4700 receivers L1/L2
- 8,5 mrad FOV	- INS – Honeywell 764 laser ring gyro
- Dual digitizers	**Digital camera:**
- Coaxial Transmitter / Receiver	- Custom built based on a Hasselblad camera with
Scanner:	a PhaseOne digital back and Sony still cameras
- Dual mirror system (Pitch and Scan)	- Resolution 3*2 k pixels, images rate 1,6 sec
- Real time controlled servo motor drive	- EO backs with 4*4 k pixel resolution can used.
Presentation:	
- Displays for pilot guidance and operator control	

Since 1999, the TopEye system has been enhanced with the capability to simultaneously capture high-resolution digital images. This makes it possible to combine the geometric data from the

Laser Range Finder with image data in either the visual spectrum or near IR. In total, eight copies of the TopEye system have been built. The system is built into a pod that is mounted beneath a helicopter. Five TopEye systems are today commercially operated by TopEye AB (http://www.topeye.com). The commercial applications include for example DTM measurements in corridors for engineering surveys roads and railroads, land development projects, city modeling, surveillance of power lines and survey of ditches. TopEye has also been the major system for Swedish research about laser scanning of forest resources.

STUDIES BY THE CENTRE FOR IMAGE ANALYSIS, SLU, UPPSALA

Tomas Brandtberg at the Centre for image analysis, SLU in Uppsala, Sweden, has used the TopEye system at the Tönnersjöheden research park in southern Sweden and also in West Virginia, USA. Starting in 1998 he developed an autonomous system for the identification of single trees in a homogenous coniferous forest in southern Sweden, using laser-scanning data (Brandtberg, 1999; 2000). The system was based on a scale-space approach in combination with a differential geometry concept, so that it was able to automatically adapt itself to the locally dominating tree crown size. An independent part of the system estimated a terrain surface of each one-hectare study area. This part was made possible by an algorithm that discriminates between canopy and ground laser points, which were modelled as two "parallel" fuzzy sets. The final ground height interpolation was able to take into account the irregularly distributed ground points. The segmentation results of individual trees in this study were encouraging, with only occasional segmentation errors. The standard error for the laser height measurements of 55 sample trees of Norway spruce was 1.4 m (Brandtberg, 2000). Fig. 5 shows an optimally Gaussian smoothed canopy surface with visible individual tree crowns on a one-hectare area of the Tönnersjöheden forest research park.

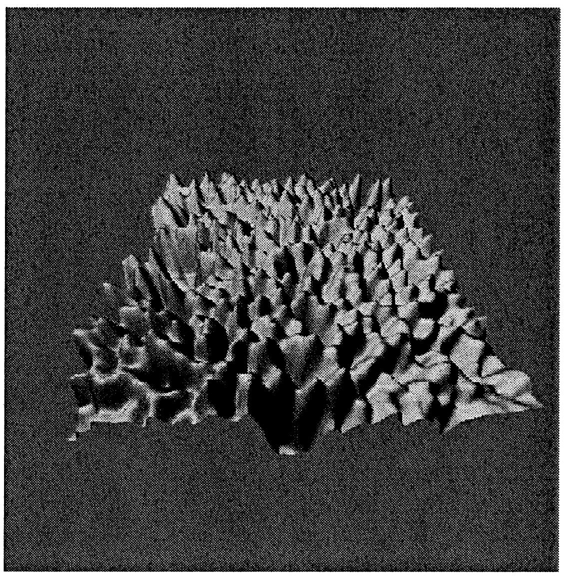

Figure 5. Canopy surface at Tönnersjöheden forest research park, Sweden, computed with scale-space techniques by T. Brandtberg, Centre for Image Analysis (CBA), Uppsala

Brandtberg continued with laser-scanning research as a Visiting Research Assistant Professor in the USA, during the years 2000-2002. In a study of deciduous forest (Oaks, Maple and Poplar) in West Virginia during leaf-off conditions, he found that individual tree crowns could be detected to some extent with a more advanced scale-space approach (Brandtberg et al., 2003) However, this forest type is comparatively more difficult to analyze. The standard error of laser height estimates was 1.1 m (N=48) and species classification of leaf-off individual trees was tested successfully using various newly defined and significant variables. This study made use of a ground reference canopy map. Furthermore, an objective method for the assessment of the individual tree-based segmentation results compared to the corresponding canopy map was developed and utilized.

RECENT STUDIES AT FOI IN LINKÖPING

FOI in Linköping has also developed methods for automatic forest mapping (ground topography; individual tree detection and measurement; and species classification) using laser scanner data as part of a program for automatic terrain mapping and 3D modelling for visualization and simulation (Persson, 2001, Ahlberg and Söderman, 2002). These methods are used to first construct a continuous ground and canopy surface model; next the individual trees are detected and measured. Finally, species classification is performed based on features derived from laser data for each detected tree. The methods was developed and tested using a data set containing dense laser data and high resolution visual and IR imagery acquired in august 2000 over Kvarn, a military training area near Linköping. The tree detection and measurement methods were validated in cooperation with SLU (Persson et al., 2002).

An investigation of the potential for future airborne laser systems in forestry applications was performed at the department of laser systems during 2000 (Steinvall et al., 2001). Existing and ongoing development of laser scanning technology and data processing, both military and civilian, was reported. In cooperation with the radar remote sensing groups at FOI, SLU and Chalmers, work has also been performed to investigate the use of high resolution laser data to complement and/or support large scale stem volume estimation using the low frequency SAR systems CARABAS (Smith et al., 2002). Laser data from the test site Remningstorp was used in this study together with VHF SAR data acquired 2000 over the same area using CARABAS. It was concluded that high resolution laser data from a few sites may be used for calibration of CARABAS backscatter to stem volume for large scale surveys. It was also concluded that combining the two technologies may be beneficial for mapping complex structured forests where the relationships between height, crown diameter and stem volume are weak or unknown. A new laser and SAR data set aimed for future investigations was obtained in summer 2002 over the Tönnersjöheden forest research park. It contains high resolution laser data from TopEye and CARABAS SAR data from more than 10 directions.

In ongoing work, investigation is also performed at FOI to improve species classification by combining laser data and aerial imagery, both available from the TopEye system. First, laser data is used to extract individual trees and to build crown segments. Next, images of the individual tree crowns are extracted by projecting the crown segments on the aerial images. The delineated crown images may then be analysed for spectral and/or spatial information for use in classification. Initial attempts have been made to extract star-shaped patterns using the theory of rotational symmetries. A preliminary classifier has been developed.

Pioneering work on terrestrial laser scanning of forest environments has been carried out both at Linköping University of Technology (Högström, 1997) and at FOI. Current tests at FOI are being performed using the ILRIS 3D scanner from Optech Inc (www.optech.on.ca). The scanner has a range accuracy of approximately 5 mm, a Field-of-View of 40°x 40°, and a spot spacing of <2,6 mm at 100 m. The maximum range is approximately 800 m (depends on material reflectivity). The data sets may be viewed as range images or "point clouds" where each measured point has a (X, Y, Z) coordinate and an intensity value. In Figure 6, two range images obtained using the ILRIS 3D scanner are shown. Depending on what part(s) of the trees that are visible in the range image(s), a number of variables can be measured directly in the images, e.g. stem diameter, tree height and crown diameter. The position of the tree relative the scanner can also be determined directly. If the scanner position is known in some reference system then the tree position can easily be determined in the same reference system.

Figure 6: From left to right are two examples of range images obtained using the ILRIS-3D terrestrial laser scanner and an example of how stem diameter can be measured in a range image.

RECENT STUDIES AT SLU IN UMEÅ

From the mid 1990's and onwards SLU in Umeå has developed methods for estimation of forest variables using laser scanner data from TopEye. The influence of laser system parameters on the estimates has also been investigated. All studies have been carried out in hemi-boreal forest at the Remningstorp test area in south western Sweden (lat. 58°30'N, long. 13°40' E).

Forest variables have mainly been estimated using regression models. On plot level, the Root Mean Square Error (RMSE) for mean tree height estimations ranged between 6% and 11% of the average value for different datasets and methods. Corresponding RMSEs for stem volume on a plot level ranged between 19% and 26% (Holmgren et al. 2003a; Holmgren 2003b). On stand level (area 0.64 ha), the RMSE was 3% and 11% of the average value for mean tree height and stem volume estimations, respectively (Holmgren 2003b). A simulation model was used to investigate the effect of different scanning angles on laser measurement of tree height and canopy closure. The effect of different scanning angles was different within different simulated forest types, e.g., different tree species (Holmgren et al. 2003c).

High resolution laser data from the Remningstorp test site have been used to detect and measure individual trees in cooperation with FOI in Linköping (Persson et al. 2002). It was found that 71 % of the trees (≥ 5 cm stem diameter), representing 91 % of the stem volume could be automatically detected, and tree height and crown diameter were measured with an RMSE of 0.6 m. The magnitude of the height estimation errors was similar to what are usually achieved using traditional field inventory methods. The tree species Norway spruce (Picea abies L. Karst.) and Scots pine (Pinus sylvestris L.) were discriminated at individual tree level with an accuracy of 95% (Holmgren and Persson 2003d). These recent studied has resulted in a PhD thesis (Holmgren 2003e).

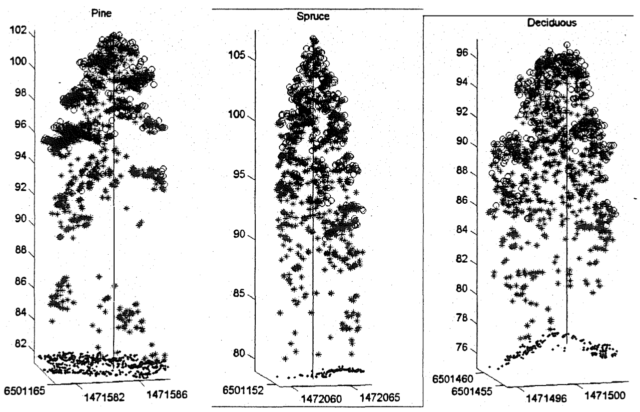

Figure 7: Laser points of a pine, spruce, and deciduous tree.

On-going work in co-operation between FOI and SLU includes tree species discrimination on single tree level between pine, spruce and deciduous trees (Figure 7) using both laser data and near infrared reflected solar radiation, registered with a digital camera. Validation of this method is planned for autumn 2003 using recently (august 2003) acquired data from Remningstorp.

CONCLUSIONS AND FUTURE OUTLOOK

As our colleagues in Finland, we have also in Sweden found that single tree level remote sensing using high density laser scanning data is possible in the boreal coniferous forest and that very good results of, for example, measurements of tree height, crown diameter, tree position, and even species discrimination, can be achieved. The rapid technical development of sensors makes it realistic to believe that single tree methods also will be economically feasible in future total area covering surveys. In combination with suitable field data, such methods are likely to improve standwise forest surveys. Furthermore, laser scanner data that only are acquired along a sample of strips might be a powerful component in future sample based field surveys. For example change detection using multitemporal laser data in a strip sampling design might be an efficient method for finding likely thinning cuttings and could therefore be useful for pre-stratification of field surveys in National Forest Inventories. It is therefore motivated that the research around single tree methods should continue. This includes extraction of more features from the laser data, combination with data from optical sensors, development of complementary field methods, and development of multitemporal methods. It can be anticipated that all four organisations that contribute to this paper will be active also in different parts of this future work.

The remote sensing group at SLU in Umeå has also come to the same conclusion as their colleagues in Norway, that low density laser scanning in combination with field data, is feasible and probably already today cost efficient for estimating mean tree heights and stem volumes at stand level. This motivates further research in complementary techniques, such as segmentation using laser scanner data and studies of optimal field sample designs. Furthermore, this also means that we are about to enter a new phase of commercial forestry laser scanning in Sweden with new organisations involved. A first sign of this is that the county forestry board in Gävleborg-Dalarna, has acquired a semi-operational laser scanner survey of a 5000 ha area where timber values should be estimated before revision of real estate borders. The scanning was carried out in May 2003 by FotoNor, using an Optech Scanner.

Finally, it must be remembered that today's commercial systems are primarily developed for other purposes than forestry. Therefore, research related to optimal system parameters for forest applications needs to be encouraged

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APPENDIX 1

Important flights in Sweden for development of methods for laser scanning of forest resources

Date	System	Test site	Research group	Area scanned (ha)	Flight height (m)	Beam divergence (mrad)	Pulse repetition frequency (Hz) and pulse density (m^{-2})	Field data
Jun 1991	FLASH / Helicopter	Ålö	SLU / FOA	4	300	2.5-10.0	160 / 0.1-1.6	28 plots
Oct 1991	FLASH / Helicopter	Ålö	SLU / FOA	4	300	2.5-7.5	160 / 0.4-1.0	28 plots
Dec 1991	FLASH / Helicopter	Ålö	SLU / FOA	4	300	2.5-10.0	160 / 0.1-1.0	28 plots
Oct 1997	TopEye / Helicopter	Remningstorp	SLU	400	240	1	7000 / 1	80 sample plots
Dec 1998	TopEye / Helicopter	Tönnersjö-heden	CBA	400	200-400		7000 / 5-10	36 plots with tree positions
Aug 2000	TopEye / Helicopter	Kvarn, Linköping	FOI	600	130	1	7000 / 15	
Sep 2000	TopEye / Helicopter	Remningstorp	SLU / FOI	400	130 / 230	1, 2, 4, 8	7000 / 5	800 tree positions 600 sample plots, 51 stands
Aug 2002	TopEye / Helicopter	Tönnersjö-heden	FOI	200	130	1	7000 / 1,4	
May 2003	Optech ALTM 2033 / fixed wing aircraft	Ovanmyra, Leksand, Dalarna	Regional board of forestry Dalarna-Gävleborg	5000	800	0,3	33000 / 1-5	sample plots, design to be determined
Aug 2003	TopEye / Helicopter	Remningstorp	SLU	1250	120 / 430	1	7 000 / 1-5	2800 tree positions 1000 sample plots

LASER SCANNING OF FOREST RESOURCES - SOME OF THE FINNISH EXPERIENCE

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ABSTRACT

Finns have participated in the development of laser scanning algorithms, processes and software rather extensively during the last 5 years. This paper describes some of the research and major results obtained.

BACKGROUND

Part of the development of laser scanning algorithms in Finland has its origins in the development work of profiling radar HUTSCAT, carried out at the Helsinki University of Technology but also within the traditional forest research. During 1986-1989 a helicopter-borne ranging scatterometer HUTSCAT was developed in order to be able to measure the backscatter of distributed targets, such as forests, at C- and X-band. After the implementation of the HUTSCAT in 1989, work continued towards the development of a scanning ranging radar and development of algorithms based on profile information. Later on the applications of the HUTSCAT in forestry have been widely published in scientific literature (Pulliainen et al., 1994, Hyyppä and Hallikainen, 1996, Hyyppä et al. 1997b; Törmä and Hyyppä, 1998).

In autumn 1997, FM-Kartta Oy organized a national meeting on the potential applications of the laser scanning. After the meeting two national projects were launched to test laser scanning in Finland: the Lidar project run by FM-Kartta Oy and another project run by the Finnish Road Administration.

After the mid of 90's, Terrasolid Oy also started their activity with laser scanning. In 1997-98, the possibilities to use TerraScan software were introduced.

In 1995-1998, a national research project MULTI was conducted in order to verify the feasibility of various data sources for forest inventory. In addition to ranging radar, aerial imagery, imaging spectrometer AISA, and satellite-based systems were applied and compared. Height information provided by the ranging radar was superior to other remote sensing data sources in volume assessment indicating high promises for forestry related applications with laser scanner. Summaries of this work can be found in (Hyyppä et al. 1997a, Hyyppä et al. 2000a).

In 1997, Andre Samberg and Juha Hyyppä collected a group of interested organizations to test high-pulse rate laser scanning to forestry. A proposal "Assessing forest stand attributes by integrated use of high-resolution satellite imagery and laserscanner" (HIGH-SCAN) was submitted to EC/IV FP/CEO by Helsinki University of Technology (LST and IPARS), Forestry Development Centre Tapio, Toposys GmbH, Joanneum Research, University of Freiburg/Felis and Scherrer Ingenierburo AG. HUT/LST had subcontracts to FM-Kartta Oy and Arbonaut Ltd. The proposal was accepted and the HIGH-SCAN was launched in the beginning of August 1998. 2-3 weeks later, the Toposys-1 system was flown in Finland within the HIGH-SCAN and the Lidar projects. Also, the Finnish Road Administration (Tapio Suominen) has had massive campaigns since 1998.

TODAY

Presently, Finns concentrate on algorithms and software development. Some of the most active organizations include

- Finnish Geodetic Institute, Helsinki University of the Technology (Institute of Photogrammetry and Remote Sensing), University of Joensuu and Helsinki University (research organizations)
- Terrasolid Oy, FM-Kartta Oy, TopTerra Oy, Helsinki and Tampere cities and Finnish Road Adminstration (companies or adminstration).

The TerraScan software (by Arttu Soininen) from Terrasolid Oy is perhaps the best-known Finnish product of laser scanning. TerraScan for MicroStation is dedicated software for processing laser scanned data. It can process tens of millions of points as all routines are tweaked for optimum performance. Processing procedures can be automated by customizing own macro programs and by using user-defined project structures. Presently, the TerraScan is assumed to be the global market leading software concerning laser scanning processing.

Also, the single tree based forest inventory using laser scanning was implemented in commercial software already in 2000-2001 (Arboreal Forest Inventory Tools) by Arbonaut Ltd. But later on the product family was sold to International Hardwood (USA).

Today, there is a good number of research projects dealing with laser scanning and forest resources in Finland, mainly run by Finnish Geodetic Institute, Helsinki University of Technology and University of Joensuu. Progress has been done in the mapping of forest resources in the following areas:

- Production of Digital Terrain Models in forested areas,
- Creation of the Digital Tree Height Models for single tree based inventories,
- Development of segmentation algorithms to retrieve single tree information from the tree height models,
- Demonstrations of single-tree-based forest inventories,
- Tree species classification,
- Reconstruction and visualization of the geometric shape of trees,
- Development of change detection methods,
- Use of theoretical distribution functions to account the suppressed trees,
- Creation of single tree models based on tree height information,
- Comparison of the laser-based inventories to inventories based on other remote sensing data
- Demonstration of laser scanning for large area forest inventory, and
- Improving the georeferencing of laser data.

EXPERIENCE GAINED

Production of Digital Terrain Models

Hyyppä et al. (2000b) evaluated and discussed the accuracy of laser scanner in digital terrain model generation and digital 3-D height model generation in forested areas. Special effort was laid to optimize the selection of ground hits used for the creation of the DTM of future high-pulse-rate laser scanners. A novel DTM algorithm was depicted in detail. To develop the algorithm, five phases were created: 1) calculation of the original reference surface, 2) removal of the vegetation from the reference surface, 3) classification of the original cloud of points, 4) calculation of the DTM based on the classified ground hits, and 5) interpolation of the missing points. Standard error of 15 cm was obtained for flat forest areas and the error increased with increasing terrain slope to the value of approximately 40 cm at the slope of 40 %. The average standard error for forest area was about 22 cm. The laser-derived DTM of the forest road deviated only 8.5 cm from the true height. An optimum performance for the DTM generation was obtained by averaging the ground hits which were located, at the maximum, 60 cm above the minimum terrain values.

The accuracy of various DEM algorithms was tested by Ahokas et al. (2002), and an accuracy of 14 cm in a hilly, forested environment was obtained for the method of Finnish Geodetic Institute. In paper Hyyppä et al. (2001), also several DEM algorithms were tested in several test sites.

Ahokas et al. (2003) studied accuracy of laser scanning in DEM production using Toposys and TopEye data. The Toposys flying altitudes were about 400 and 800 m above ground and for the TopEye, 100, 200, 400 and 550 m flying altitudes were used. Reference measurements on the ground were made with a RTK GPS and a tachymeter. Points on asphalt, grass, gravel and forest ground were measured. Height errors for different surfaces were calculated. The higher the flying altitude, the larger was the height error. All the three comparison methods (ALS mean height in the test circle, height of the nearest laser point and interpolated height) seemed to give similar results for the mean of differences (reference height – ALS height) in the same flight line. There were also quality differences between flight lines. Height errors as a function of observation angle were determined. Observation angle had an effect on the height accuracy. A systematic error of typically 10 cm was observed due to observation angle changes. Different R-squared values (coefficient of determination in the regression analysis) were obtained for the same surface material at different flying altitudes.

Hyyppä and Engdahl (1999) verified various digital elevation models using laser-derived DEM as the ground truth. Models were also created to understand the response of SAR on forest areas.

Creation of the Digital Tree Height Models for single based inventories

In Yu et al. (2003), the tree height model was computed as the difference between the digital surface model (DSM) representing the top of the crown and the digital elevation model (DEM). The DSM of the crown was obtained by taking the highest elevation value (z value) of all laser hits within each pixel (50 cm). The value for missing pixels was obtained using Delaunay interpolation. Hits coming beneath the crown surface may be valuable for biodiversity information but are not needed in the construction of tree height models. To generate a DEM from laser scanner data, points that reflected from non-ground objects were classified. This technique has shown to give tree height accuracies of about 50 cm (Yu et al. 2003).

Development of segmentation algorithms to retrieve single tree information from the tree height models

The segmentation algorithms of HUT (subcontract from Arbonaut Oy), FELIS (University of Freiburg) and JR (Joanneum Research) were applied to a small test site in Hohentauern (Austria), where nearly 200 trees were measured terrestrially (Hyyppä et al. 2001a). For verification purposes, 197 single trees irregularly distributed within the test site (8 reference areas with 15 – 30 trees measured within the area) were surveyed by ground measurements. The exact position of the single trees was determined by the use of differential GPS system and terrestrial measurements. Further, the tree crowns of the reference trees were delineated in field; the stem diameter, tree height and tree species were recorded. The reference areas were homogeneous with regard to crown closure. The 197 reference trees consisted of 165 spruces, 25 larches and 7 other coniferous trees. The JR algorithm delivered slightly better results with 50 % correctly segmented crowns compared to 40 % of the HUT algorithm and 44 % of the FELIS algorithm, as the JR algorithm was developed for the conditions of test site Hohentauern. For the JR and the HUT algorithms errors were mainly caused by merged crowns due to non-detection of shadowed trees and missing maximum due to oversmoothing. With the FELIS algorithm, the main errors occurred by not segmenting certain trees at all.

Demonstrations of single-tree-based forest inventories

The basic idea of the single-tree-based forest inventory is that the calculation of the stand attributes for a single stand is based on the measurement of the location, tree height, species and crown area for each single tree. From that information, all other stand characteristics are derived.

The location, tree height and tree crown areas can be obtained from laser scanner data, whereas the tree specie is obtained from image data.

In Hyyppä and Inkinen (1999) and Hyyppä et al. (2001b), it was demonstrated that high-pulse-rate laser scanners are capable to detect single trees in boreal forest zone, and characteristics of single trees, such as height, location, and crown dimensions can be determined providing accurate standwise estimates for stem volume and mean height. By increasing the number of pulses, it was possible to have samples from each individual tree and also from the gaps between the trees. Basically this meant that several laser pulses were recorded per m^2. Tree height model was calculated from the digital terrain and crown models both obtained with the laser scanner data. By analysing the 3-dimensional tree height model by using image vision methods, e.g. segmentation, it was possible to locate individual trees, estimate individual tree heights, crown area and, by using that data, to derive the stem diameter, number of stems, basal area and stem volume. The advantage of the method was the capability to measure directly physical dimensions from the trees and use that information to calculate the needed stand attributes. It was shown that tree heights of individual trees in the dominating storey could be obtained with less than 1 m standard error. In addition, the following standard errors were obtained for mean height, basal area and stem volume at stand level: 2.3 m (13.6 %), 1.9 m^2/ha (9.6 %), and 16.5 m^3/ha (9.5 %), respectively. The accuracy was better than the accuracy of conventional standwise field inventory.

The effect of pulse density to single tree based forest inventory has also been studied. The pulse rate was deteriorated by randomly taken the needed amount of pulses. Consequently, pulse densities of 1, 4 and more than 10 pulses per square meter were created. Window sizes of 13, 9 and 9 m were applied in minimum filtering of the DTM process. Resolution of 1 m was taken for pulse densities of 1 and 4 pulses per square meter. Digital tree height model was calculated for each data set separately, and new segmentation was carried for each data set. Stands with data holes were removed. Even though, the number of stems was significantly reduced using lower amount of pulses, and therefore, larger segments were created. The underestimation increased, but the standard deviation of the results did not basically deteriorate at all with lower pulse rates. Most probably explanation for the results are that with 1 pulse per square meter the distribution of the pulses is more spatially spread than with higher pulse rates. E.g. with pulse density of more than 10 pulses, most of the performance is deteriorated due to the oversampling of Toposys-1 in along track direction. Most probably with lower pulse rates, such as with 1 pulse per square meter, and keeping the orientation of pulses similar with Toposys-1, we obtained results with significantly lower accuracy.

Tree species classification and integration of image data

Antero Kukko tackled the species classification using both the geometrical shape information of laser scanning and image data of aerial photographs. First the aerial photographs were orthorectified using the DSM corresponding to the top of the crown. An accuracy of 79 % was obtained for species (pine, spruce and birch) of individual trees.

Törmä (2000) employed multiplayer perceptron neural network with back-propagation training algorithm to estimate tree species proportions at stand level. Only data source was from laser scanning. The classification accuracy of 66 % was obtained at the best.

In Hyyppä et al. (2001a), it was reported that the classification result using Ikonos for tree species showed almost perfect delineation of broad-leaf forest/ trees. The use of Ikonos image in the boreal forest zone does not seem to be an easy task. Due to rainy summer, the image was taken in late autumn and early in the morning, therefore there are long shadows in the image. However, at stand level the overall accuracy for main tree species was about 88 %.

The data integration of image data and laser data has been carried out by object-oriented data integration for stand wise estimates. Segments were obtained from laser data. These segments were considered as objects, the characteristics of which were collected both from image data and from laser data. Height and canopy area could be obtained using laser-derived tree height data, and the tree species was obtained from the aerial imagery. Models to calculate the stem volume based on tree height, stem diameter and tree species were applied.

Reconstruction and visualization of the geometric shape of trees

The objective the study by (Pyysalo and Hyyppä, 2002) study was to carry out reconstruction of single tree crowns from laser scanner data to use the obtained vector model for feature extraction. The reconstruction was implemented in several stages. First, pulses reflected from individual trees were marked off from the original point cloud. Ground points were then separated from all points using digital terrain model and analyzing the histogram of terrain height values. In the next stage canopy was described with vector polygons, and the location of the trunk was estimated. With respect to the location of the trunk, tree points were transferred from *(xyz)*-co-ordinate system to the polar-co-ordinate system *(a,r,h)*, and features were estimated from the vector model. Evaluation of the reconstruction was performed choosing a test area and processing 50 single trees, and comparing results to the field measurements. In the study it was found that dense laser scanner data detail describes the upper canopy of forest and therefore is suitable for tree height information extraction. The lower crown was found less detail measured with laser scanner and parameters extracted from that part were less accurate, but trend setting. Obtained distance profile seemed to give tendency for the tree specie.

Development of change detection methods

The applicability of small footprint, high sampling density airborne laser scanner for estimation of forest growth and detection of harvested trees was demonstrated by Yu et al. (2003) Two laser acquisitions - one in September 1998 and another in June 2000 - were carried out using Toposys-1 laser scanner in test site (Kalkkinen), 130 km north of Helsinki. Three-dimensional tree height models were calculated for both data sets using raster-based algorithms. Object-oriented algorithms were developed for detection of harvested trees and forest growth estimation. Out of 82 field-checked harvested trees, 65 trees could be automatically detected. All mature harvested trees were detected; problems were encountered mainly with smaller trees. Forest growth was tested at tree, plot and stand levels. Applied methods included an object-oriented tree-to-tree matching algorithm, interactive orientation using point cloud and statistical analysis. The precision of the estimated growth, based on field checking or statistical analysis, was about 5 cm at stand level and about 15 cm at plot level.

Use of theoretical distribution functions to account the suppressed trees,

Maltamo et al. (2003) proposed the use of theoretical distribution functions to account for the suppressed trees. The tree crown segmentation method used cannot detect suppressed trees from a height model based on laser scanning. Consequently, the shortest trees of the dominant tree layer may not be recognized. These trees can be predicted by using theoretical distribution functions. In study by Maltamo (2003), two different methods were used to predict small trees. First, the parameter prediction method was utilized with the complete Weibull distribution, the parameters of which were predicted with separate parameter prediction models; and thus, small trees were determined from the predicted tree height distribution. In the second method, the two-parameter left-truncated Weibull distribution was smoothed to the detected tree height distribution. For the calculation of plot volumes, individual tree volumes were predicted by using the existing national volume models, which were based on the diameter at breast height and total tree height. However, before the volume models were applied, diameters at breast height were calculated for all trees. They were calculated from the diameter prediction model, the independent variables of which were the tree height and crown area or the tree height only.

Creation of single tree models based on tree height information,

Single tree based models based on height information have been developed at University of Joensuu and University of Helsinki.

Comparison of the laser-based inventories to inventories based on other remote sensing data

The laser-based estimates have been compared with estimates produced by other airborne and satellite-borne remote sensing data on the retrieval of the following forest stand attributes: stem volume (m^3/ha) and mean tree height (m). Information content of the following data were compared: Landsat TM, SPOT Pan and XS, airborne data from imaging spectrometer AISA and laser scanner TopoSys-1 in a single test site, Kalkkinen. The adjusted coefficient of determination, the corrected standard error of the model, and the standard errors in percentage were calculated for each data source. All the data were used for the model development. The data sources in the estimation of tree height in the decreasing order of explanation power were the laser scanner, imaging spectrometer AISA, Landsat TM, Spot XS and Spot Pan and in the estimation of stem volume the corresponding order was the laser scanner, imaging spectrometer, SPOT XS, Landsat TM and Spot Pan. The SE% obtained in the stem volume estimation for laser was 13.5% compared to 49.6 % for Spot Pan. Laser scanner was the only data source of equivalent or better accuracy with the traditional forest inventories. (Hyyppä and Hyyppä, 1999)

Demonstration of laser scanning for large area forest inventory

A continuous forest/agricultural area (85 km^2) was measured for the Finnish Geodetic Institute in spring 2003 by Toposys-2 (Falcon). The area will be used for demonstration of large area forest inventory.

Improving the georeferencing of laser data.

The interactive orientation method is depicted in Rönnholm et al. (2003). Interactive orientation is suitable for traditional orientation tasks, when accurate 3D reference data, e.g. points or lines, exist. Rönnholm et al. (2003) presented algorithms for interactive orientation between panoramic images and existing 3D data. The method is based on visual interpretation of the data obtained by superimposing laser scanning data on 2D images. The interactive orientation method gives an excellent opportunity to inspect the behavior of laser scanning. By backprojecting a laser scanning data onto the oriented image, it is easier to understand the point clouds of laser scanning.

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A LARGE FOOTPRINT LIDAR WAVEFORM MODEL FOR FOREST

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ABSTRACT

Large footprint lidar has demonstrated its great potential for accurate estimation of many forest parameters. Especially it can rebuild the vetical structure of forest canopy. But there are many uncertainties in the interpreting of lidar waveforms because of the atmosphere effects, the under canopy's contributions, the shape of crown, et al. A waveform model can help us understand these effects better and estimate forest parameters more accurately. In this study, a large footprint lidar waveform model for 3 dimensional forests was introduced and used to simulate the GLAS waveforms from a measured forest stand.

INTRODUCTION

Vegetation spatial structure including plant height, biomass, vertical and horizontal heterogeneity, is an important factor influencing the exchanges of matter and energy between landscape and atmosphere, and biodiversity of ecosystems (Dubayah, et al., 1997). Most remote sensing systems and techniques, although providing images of the horizontal organization of canopies, do not provide direct information on the vertical distribution of canopy elements.

Laser altimeter systems have been developed to provide high-resolution, geolocated measurements of vegetation vertical structure and ground elevations beneath dense canopies. The basis of the method is ranging to the surface obtained by precise timing of the round-trip travel time of short-duration pulses of backscattered, near-infrared laser radiation (Sun and Ranson, 2000). Over the past decade there have been dramatic improvements in LiDAR technologies and the technology has been used successfully to estimate many forest parameters. Canopy height, basal area, canopy density and biomass have all been successfully derived from lidar data (Nilsson, 1996; Means et al, 1999; Popescu et al, 2002; Lefsky et al, 1999; Drake et al, 2002; Lim et al, 2002).

With recent technological advances in lidar remote sensing and the developments of quantitative remote sensing, it becomes increasingly important to understand the physics of photon propagation through the vegetation canopies. A lidar waveform model depicting the interaction between the laser energy and the elements of canopy can be used to explore the relationship between lidar waveforms and canopy structure parameters, help us take full advantage of the information contained in the lidar waveforms. During the past several years, there were several lidar waveform models of forests which simulated the forest lidar waveforms with different methods. Blair first modelled the waveforms as the sum of the reflections from individual surfaces within laser footprints (Blair and Hofton, 1999). Sun developed a 3-D model to simulate the lidar waveforms from forests (Sun and Ranson, 2000). Ni-Meister used the geometric optical and radiative transfer (GORT) model to describing the lidar waveform from forests and analyzed the clumping effect in the simulated waveforms (Ni-Meister et al, 2001). These models only consider single scattering mechanism. Kotchenova modelled the lidar waveforms with time-dependent stochastic radiative transfer theory, which included the multiple scattering mechanisms and got better results over density forests (Kotchenova et al, in press).

The Geoscience Laser Altimeter System (GLAS) (Fig. 1) is a NASA Earth Observing System facility instrument aboard the Ice, Cloud and land Elevation Satellite (ICESat) launched on 13 January 2003. It is the only operational spacebore lidar sensor now. GLAS is a large footprint waveform lidar and operates continuously in a 600 km, 94 degree inclination orbit, acquiring globally distributed elevation profiles consisting of 70 m diameter laser footprints spaced every 175 m along the profile. This paper will focus on simulating the forest lidar waveform with GLAS' parameters using Sun and Ranson's 3D lidar waveform model and analyze the GLAS' feasibility to estimate forest structure parameters.

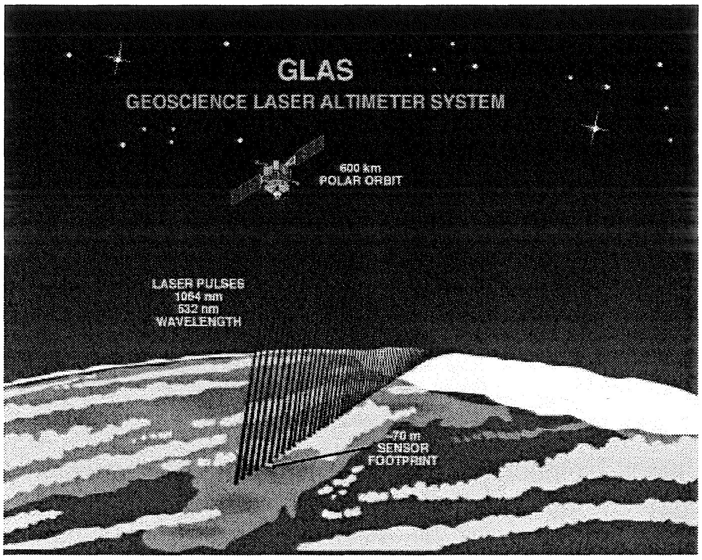

Figure 1. Geoscience Laser Altimeter System (GLAS) (From utexas GLAS web site: http://www.csr.utexas.edu/glas/

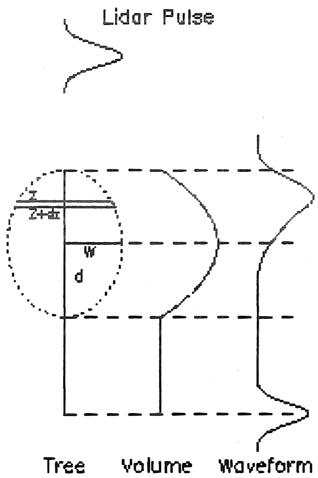

Figure 2. Schematic of lidar pulse and waveform from a single tree with ellipsoidal crown. The middle curve is the canopy volume distribution

METHODS

Basic Canopy Lidar Equation

Canopy Lidar records the range and intensity of returns reflected from all levels through the canopy. A lidar sends out a short duration laser pulse. The digitizer samples the detector output voltage of returned signal from targets at a certain rate, yielding a waveform for that laser shot (Harding et al, 1998). This waveform is a record of return signal as a function of time.

$$R = \frac{c \cdot t}{2} \qquad (1)$$

with R the distance between the sensor and the object surface, c the speed of light and t the interval time relative to a specific point on the laser pulse (Baltsavias, 1999). The vertical sampling resolution depends on the duration of the digitizer bin. So the vertical resolution of waveform is:

$$\Delta R = \frac{c \cdot \Delta t}{2} \qquad (2)$$

with ΔR the vertical resolution and Δt the duration of the digitizer bin.

Treewise Lidar Waveform

Fig. 2 illustrates a laser pulse and the resulting waveform after it hits a tree. The tree crown here was modeled as an ellipsoid with half-length *d* and half-width *w*. To describe the scattering and attenuation properties of a scattering medium, terminology adopted from Natsuyama et al (1998) will be used here. The scattering coefficient σ is defined such that σdz equals the fraction of energy scattered by the materials in the medium as a beam of radiation travels through a cylinder of unit cross-sectional area and height *dz*, per unit mass of the matter. The attenuation coefficient α can be defined similarly. The ratio σ/α is the single scattering albedo. If we use ν = ν(z) to represent the density of the medium as a function of vertical position z, (equivalent to the vertical distribution of intercepted surfaces to be retrieved from a lidar), then the optical depth τ of the medium from *z=0* to *z=z* will be $\tau = \int_0^z \alpha v(z)dz$ and the scattering from a slab between *z* and *z+dz* will be $\Omega = v(z)\sigma dz$. The energy scattered from this slab (with unit area) and reaching the top of the canopy (*z=0*) can be expressed as: $I = I_0 e^{-2\tau}\Omega$, where I_0 is the incident radiation.

In our current study, only first-order scattering was considered. The backscattered energy from a horizontal slab with unit surface area and thickness Δ*z* at depth *z* can be expressed as:

$$L = L_0 e^{-2\alpha \int_0^z v(z,s)dz} v(z,s)\sigma dz \qquad (3)$$

where L_0 is the incidence laser intensity. Here we assume that the density of medium can also be a function of horizontal position (s). The exponential term accounts for the two-way attenuation from the part of tree crown above this slab. For an uniform ellipsoidal crown, i.e. ν, σ, and α are constants, the energy scattered from a crown slab of thickness Δz at *z* and reaching the top of crown can be analytically calculated by the following integration:

$$L = L_0 2\pi\sigma v \int_z^{z+\Delta z} dz \int_0^{\frac{w}{d}\sqrt{(d^2-z^2)}} e^{-2\alpha v(\frac{d}{w}\sqrt{w^2-r^2}-z)} rdr \qquad (4)$$

where d and w are the half length and half width of the ellipsoid crown. The time delay of this signal will be the time for light to travel from lidar to position z The time delay of this signal will be the time for light to travel from lidar to position zand back to lidar. The backscattered signal may also be presented according to the height from ground surface. The modeling results will be plotted with respect to the height above ground surface.

Standwise Lidar waveform model

Ideally, the laser pulse should be of rectangular shape and with infinitesimal duration to ensure accuracy and high vertical resolution. In practice the laser pulse has a curved shape and finite duration. Generally, the pulse width is much larger than the signal digitization interval, every scatterer will produce a signal which is recorded in many bins. Each signal bin corresponds to an assumed rectangular pulse with the duration or pulse width equal to the thickness of the crown slab cell. The total signal will be the summation of these bin signals according to their time delay.

The model inputs include diameter at breast height (dbh), height, and species for each tree in the stand. The crown shape, and crown structure may be determined from these parameters according to the allometric equations. The attenuation and scattering properties of a cell can be estimated from the phase function of individual tree components by integration over the orientation distributions of these components (Gastellu-Etchegorry, et al., 1996). The three-dimensional scene is divided into cells according to the vertical resolution of the lidar. Let z=0 be the top of the stand, and z increases downward from the canopy top. If the canopy cell is small, i.e. both Δz and Δs are small, we can assume that the density of scattering medium is constant within this cell (see Sun and Ranson, 2000 in more detail).

The canopy was divided into m layers (Cj, j=1, m from top to bottom, with thickness Δz) and the lidar pulse was divided into n narrow pulses (Li, i=1, n from front to tail, with duration Δt=2Δz/c, c is the speed of light). If the lidar return signal starts when the pulse L1 reaches the sub-canopy layer

C1, the time delay for pulse Li to hit canopy layer Cj and return back towards the lidar will be (without counting the time delay between lidar and upper canopy surface):

$$t(i,j) = 2(i+j)\Delta z / c \qquad (5)$$

where c is the speed of the light. The returned signal will be:

$$L(i,j) = L_i \sigma v_j \Delta s \Delta z e^{-\alpha \sum_{k=1}^{j-1} v_k \Delta z} = L_i \Omega_j \mathrm{E}_{j-1} \qquad (6)$$

where $\Omega_j = \sigma v_j \Delta s \Delta z$ is the backscattering from a cell at jth canopy layer, E_{j-1} is the extinction above this cell, and L_i is the ith lidar sub-pulse.

The lidar waveform is recorded in (m+n-1) digitizing bins. The time delay intervals for these bins are: [0, 2Δz/c], [2Δz/c, 4Δz/c], ... [2(m+n-2)Δz/c, 2(m+n-1)Δz/c]. The first interval is when the first (top) canopy layer reflects the first lidar sub-pulse (front of the lidar pulse). Each lidar sub-pulse will produce a series of returns as shown in Eq. 6. The signals from these sub-pulses need to be added to proper bins according to the time delay. Following is the list of components in these bins:

$$\left| \begin{array}{llllll} 1: & L_1\Omega_1 & & & & \\ 2: & L_1\Omega_2\mathrm{E}_1 & +L_2\Omega & & & \\ n: & L_1\Omega_n\mathrm{E}_{n-1} & +L_2\Omega_{n-1}\mathrm{E}_{n-2} & +L_3\Omega_{n-2}\mathrm{E}_{n-3} & +\ldots & +L_n\Omega_1 \\ m: & L_1\Omega_m\mathrm{E}_{m-1} & +L_2\Omega_{m-1}\mathrm{E}_{m-2} & +L_3\Omega_{m-2}\mathrm{E}_{m-3} & +\ldots & +L_n\Omega_{m-n+1}\mathrm{E}_{m-n} \\ m+n-2: & & & & L_{n-1}\Omega_m\mathrm{E}_{m-1} & +L_n\Omega_{m-1}\mathrm{E}_{m-2} \\ m+n-1: & & & & & L_n\Omega_m E_{m-1} \end{array} \right| \qquad (7)$$

Every column of cells of a footprint will produce a series of signals listed in Eq. 7. The lidar waveform of this footprint is the sum of these signals according to their time delay. When these waveforms are plotted, the signal from the peak of the laser pulse will be registered with the height of the scatterer (Fig. 2). So the scattering (reflectance) from a flat surface (ground) would appear as a Gaussian-shaped waveform with peak at the height of the surface level as shown in Fig. 2. It should also be noted from Fig. 2 that the peak of the waveform due to crown leaf reflectance does not coincide with the peak of crown volume vertical distribution.

RESULTS

According to the method discussed above, we use the GLAS' parameters and a measured forest stand parameters of BOREAS to simulate the waveform from forests.

Measured forest stand parameters

At the BOREAS Southern Study Site, Prince Albert, Saskatchewan, Canada, trees within a 1-ha (100 m by 100 m) mature stand of jack pine were measured (Fig. 3). The stem location, dbh, species, and relative canopy position (e.g., dominant, co-dominant, intermediate, suppressed) were recorded for each tree in the stand in September 1993. Only trees with a dbh greater than 2.5 cm were measured for a total of 1900 trees. In addition, total height, crown length and crown width were measured from jack pine trees as part of the BOREAS field activities.

Regression relationships for calculating tree parameters, and the scattering and attenuation coefficient used in simulations are listed below:

Height (m) = 20.98 * LOG10(DBH(cm)) – 10.09, r2 = 0.98, N=275

Crown-length (m) = 0.432 * Height (m) + 1.48, r2 = 0.94, N=200

Crown-width (m) = 0.222 * Height (m) – 0.162, r2 = 0.93, N=46

Crown scattering coefficient – 0.515, Transmittance coefficient – 0.305, Ground reflectance – 0.29

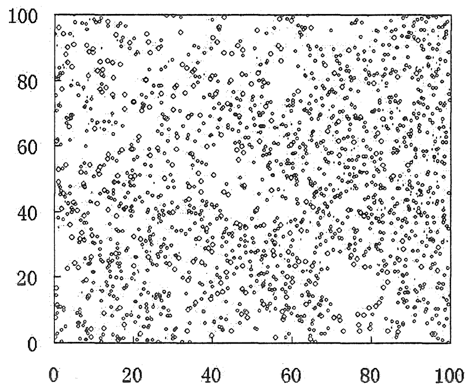

Figure. 3. Stem map of a forest stand at the BOREAS Southern Study Site, Saskatchewan, Canada. Small circles represent the relative DBH of trees, but not in the scale of the plot axes. The large circle is the lidar footprint (70 m in diameter) for waveform simulation.

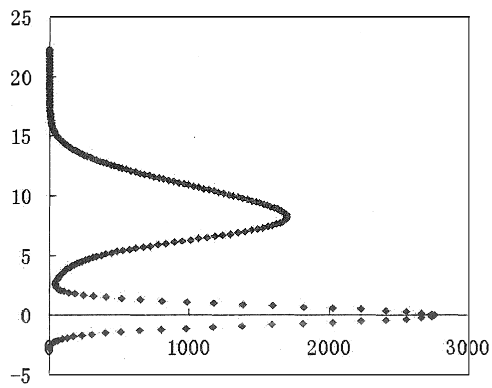

Figure. 4. Simulated GLAS lidar waveforms for the Jack Pine stand.

Lidar system parameters

The GLAS instrument uses a laser altimeter to measure the range to the surface. Ranges are determined from the measured time between transmission of the laser pulse and detection of the photons reflected from the surface and received by the instrument. The laser footprint diameter on the surface is nominally 70 m, and the width of the transmitted pulse is 4 ns, equivalent to 60 cm in surface elevation. The detected pulse corresponding to the reflections from the surface is selected by an instrument algorithm and digitized in 1 ns (15 cm) range bins (Brenner et al, 2000). The laser with 1064 nm wavelength was used in the model.

Glas waveform simulation from a jack pine forest stand

In the model, the crown shape is modeled as cone. In the simulations conducted in this study, the following assumptions were made: 1) uniform crown, i.e., all crown cells have the same scattering coefficient and transmittance, 2) uniform ground surface, i.e., the ground surface within the footprint is flat and has the same scattering coefficient, 3) only single scattering was considered. Lidar pulse with Gaussian shape, such as that shown in Fig. 2 was used.

The simulated waveform is shown in Fig. 4. The MaxH (18.4 m) in the footprint very closely matches the first return signal in the simulated lidar waveforms (17.5 m) (Fig. 4). So we can see that even the very large footprint lidar (e.g. GLAS 70 m), it is still feasible to estimate the forest parameters with the lidar waveform data. But it is notable that the footprint size is so large that the topographic fluctuation within the footprint should be considered in some cases.

CONCLUSIONS AND DISCUSSIONS

The three-dimensional model for simulating lidar waveforms from forest stands was used to simulate lidar waveform of GLAS. The preliminary comparisons between simulated lidar waveforms and the input forest stand parameters show that the GLAS waveform data can be used to estimate the forest stand parameters.

In our future work, we will add the multiple scatter mechanisms and the rough surface effects to improve this model. Validate the simulated results with GLAS data after they are available. Then the model will be used to study the relationship between forest physical parameters and the lidar waveforms for development of retrieval algorithms.

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ESTIMATION OF FOREST STAND PARAMETERS USING AIRBORNE LASER SCANNER DATA: A COMPARISON OF METHODS

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ABSTRACT

Partial least squares regression (PLSR) as a technique for modelling forest-stand parameters by means of airborne laser scanner is analysed. Models for predicting mean height (hL), dominant height (hdom), mean diameter (dg), number of stems (N), basal area (G) and stand volume (V) have been developed. The basis for the models is data obtained by airborne laser scanner and corresponding field sample plots. PLSR is used to establish the relationships between field data and various canopy height- and canopy density metrics derived from laser data. The models derived are compared to models developed by means of stepwise regression methods, hereafter referred to as OLS models.

A comparison of validation results for the two types of models reveals that they give fairly similar results with respect to mean prediction error. For the stratum-specific PLSR predictions, standard deviations of the differences between predicted and observed values of hL, hdom, dg, N, G and V were 0.81-1.14 m, 0.71-1.58 m, 1.05-1.50 cm, 122-139 ha^{-1}, 3.91-5.99 m^2ha^{-1} and 33.6-56.8 m3ha-1, respectively.

In this particular study, it is not possible to draw any strong conclusions about which model form that best is able to handle the laser data. In an overall perspective, however, the PLSR is a versatile method dealing with data material where there is little or no causal information read directly from the data. Martens & Martens (2001) points out that one of the strengths of PLSR is that the method allows the data to speak for themselves, outside the “cage” of prior theory. Thus, further analysis using PLSR is regarded to be of interest.

INTRODUCTION

Three-dimensional information about tree canopies obtained by means of airborne laser scanner, is a valuable contribution to forest inventory. It has been indicated that a utilization of different canopy metrics computed from laser data can give more precise estimates of essential stand parameters than a traditional field inventory (Næsset 1997a, 1997b, 2002). In order to acquire these estimates, a model that establishes the relationship between laser data and the field parameters of interest is necessary. Usually, multiple regression models based on ordinary least squares (OLS) have been developed, but the characteristics of the data in question suggest that other statistical methods must be considered.

In many statistical analyses of data containing many dependent variables, principal component analysis (PCA) is used to reveal the variance- and covariance structures hidden in the data. However, PCA is not applicable to parameterise a predictive model, but the principles behind are embedded in other techniques like the partial least squares regression (PLSR). PLSR is a versatile statistical method used in many fields of science, and is especially useful for exploring datasets that contain many dependent variables. Hence, this method is interesting with respect to modelling on laser data.

This paper presents a comparison of OLS (stepwise regression) and PLSR with respect to predictive ability. Both OLS and PLSR models are derived from the same data, and are validated on the same independent dataset. The basis for appraisal is prediction error with corresponding test of significance. The comparison is done for predictions of six different parameters in two different strata. The parameters are mean height (hL), dominant height (hdom), mean diameter (dg), number of stems (N), basal area (G) and timber volume (V).

MATERIALS AND METHODS

The estimation data originate from 77 circular georeferenced field sample plots of 232.9 m^2 in Krødsherad (60º 10´N; 9º 35´E, 130-660 m a.s.l) in the southeast of Norway. The forest area in question totals to 6500 ha, of which 5000 ha are classified as productive, i.e. have an increment > 1 $m^3ha^{-1}yr^{-1}$.

Data were collected as part of a large-scale practical forest inventory. By means of stereoscopic photo interpretation from this inventory the stand perimeters were delineated, and tree species, site index and age class were determined, where the two latter parameters constitute the criteria for classifying the stands into two strata. Stratum 1 corresponds to mature conifer forest with poor site quality and stratum 2 is mature conifer forest with good site quality. Poor site quality was assigned to sites with H40 site index less or equal to 11. The H40 index is defined by average age at breast height and the average height of the 100 larges threes per ha according to diameter at breast height. The specific value of the H40 site index relate to the dominant height at an index age of 40 years (Braastad 1980, Tveite 1977). The number of plots related to each stratum are 38 and 39, respectively.

Ground-truth data were collected during summer 2001. All trees with diameter in breast height (dbh) > 10 cm were callipered on each of the 77 plots. Heights where measured on trees selected by a relascope, and a basal area weighted mean height (hL) (Lorey`s mean height) was computed. Dominant height (hdom) of each plot was computed by taking the arithmetic mean height of the 100 largest trees per hectare according to diameter. Thus, the two largest trees according to diameter were used to compute the dominant height on the 232.9 m^2 plots. Mean plot diameter (dg) was computed as mean diameter by basal area for trees with dbh > 10 cm. Stem number (N) was computed accordingly as number of trees per hectare. From the breast height measurements, the plot basal area per hectare (G) was computed. Individual tree volumes were computed by means of volume equations. Total plot volume (V) was computed as the sum of these individual tree volumes. Table 1 displays the mean values and range for the sample data.

Table 1. Summary of sample plot data

	Stratum 1: n=37		Stratum 2: n=33	
	Mean	Range	Mean	Range
h_L (m)	15.1	9.9-23.3	20.3	14.4-26.1
h_{dom} (m)	16.7	10.4-28.9	22.9	16.8-30.2
d_g (cm)	22.3	14.7-32.5	23.9	17.5-34.1
N (ha^{-1})	628	172-1632	803	301-1503
G (m^2ha^{-1})	22.6	5.6-42.7	34.2	15.5-57.0
V (m^3ha^{-1})	175.1	29.6-428.9	340.8	120.1-675.7
Tree species distribution (%)				
Spruce	19	0-100	58	0-100
Pine	77	0-100	37	0-100
Decid[a]	4	0-22	5	0-29

a) Deciduous species.

The validation data originate from 38 quadratic georeferenced field plots with an average size of approx. 0.37 ha. Within each validation plot, diameters were callipered and tree heights were measured in the same manner as the sample plots. Mean height, dominant height, mean diameter, stem number, basal area and volume were computed by means of these measurements.

From the laser measurements of each sample- and validation plot, first and last pulse height distributions were created. These distributions were the basis for deriving the explanatory variables which include mean values, coefficients of variation, percentiles of the canopy heights for 0%, 10%,…, 90% and several measures of canopy density. The range between the lowest laser canopy height (>2 m) and the maximum canopy height as derived from the first pulse canopy height distribution was divided into 10 fractions of equal length. Canopy densities were then computed as the proportions of laser hits above fraction # 0 (>2 m), 1,..., 9 to total number of pulses. This was done for both the first- and last pulse data.

Model estimation principles

The main goal for this study was to investigate the predictive abilities of the partial least squares regression (PLSR) (Martens 2001, Martens & Martens 2001, Wold et al. 1983) methods. To make inferences about candidate models, different criterions are considered. The main basis for appraisal is, however, a comparison of validation results using the PLS- and OLS models.

PLSR

The characteristics of data obtained by laser scanner are mainly the motivation for modelling with PLSR. Laser data may contain many variables (post-processed height measures). In such data, the level of collinearity can be high, and building a complex model on such basis may be difficult or impossible. A "traditional" model form may therefore not to the full extent be able utilize all information stored in the data because of dependency between variables, but also because it may be difficult to interpret the causal relationships. PLSR is based on extracting a few linear combinations (PLSR components) that encapsulate the relevant variance from a set of explanatory variables such that they explain one or many dependent variables the best possible way. Furthermore, every PLSR component will account for different types of variance, meaning that the variables that explain one specific characteristic will be of great importance in one component. All PLSR components are uncorrelated, and the first extracted component is the linear combination with maximizes the covariance between the dependent variables (Y) and the regressors (X). The second component is the linear combination which maximizes the covariance between Y and X after extracting the first, and so on. Utilizing these qualities makes it easier to analyze datasets containing many variables with little or no causal interpretation. The PLSR procedure can step by step be summarized in the following way (Martens & Martens 2001): Firstly, enough response-relevant PLSR components from X must be extracted so that most of the variation is explained. Then the second step is to determine the optimal number of PLSR components (A) by cross validation where the objective is to minimize the prediction error. Determining the optimal number of PLSR components is important because PLSR models easily are overfitted. Each observation's contribution (magnitude of importance) in each component (X-scores = ti) are then stored in a matrix T=(t1, t2,..., tA). T is in the third step used to model X in terms of each variable's importance in each component P (X-loadings), and E (X-residuals), formulated as

$$X = TP^t + E \tag{1}$$

The fourth step is to model the responses (Y) by means of T, Y-loadings and Y-residuals, where the two latter are denoted Q and F, respectively. This yields

$$Y = TQ^t + F \tag{2}$$

A regression coefficient matrix (B) can be made from P and Q. This yields a model for predicting Y directly from X.

$$Y = XB + F \tag{3}$$

A preliminary analysis, i.e. principal component analysis (PCA) and appraisal of candidate models by cross validation, was firstly carried out to disclose any special properties in the data. First, it was by means of the X-scores determined whether the models should be stratified. Second the loadings for each dependent variable were analysed to look for similarities. In the PLSR procedure, models for many responses can be estimated simultaneously. However, it is crucial that the responses reflect similar information in order for a simultaneous estimation to be advantageous. Last, the optimal number of PLSR components (A) was determined for all models individually. Every component had to satisfy a significance level of 0.1, or else regarded as noise. Final models were estimated using the partial least squares procedure in SAS (Tobias s.a).

OLS

Multiple regression analysis is used to derive multiplicative models. These models were estimated as linear regressions on logarithmic transformed data. The multiplicative models were in general formulated as

$$Y = \beta_0 X_1^{\beta 1} X_2^{\beta 2} \ldots X_k^{\beta k} \quad (4)$$

whereas the linear form used in the estimation was

$$Y = \ln\beta_0 + \ln\beta_1 X_1 + \ln\beta_2 X_2 + \ldots + \beta_k X_k \quad (5)$$

where Y represent the field values h_L, h_{dom}, d_g, N, G or V. $X_1, \ldots, X_k$ represent the explanatory variables computed from the laser pulse distributions.

The final explanatory variables were selected by stepwise regression. In order to be a part of the models, every variable had to meet a significance level of 0.05. Number of selected variables ranged from 1 to 4. Subsequent to the selection of variables, the final regressions were converted back to original scale. The intercept was adjusted by adding half the estimated variance before conversion (Goldberger 1968).

Validation

To assess the predictive abilities of the OLS- and PLSR models, they are validated on independent data. For each validation plot, 16 sub plots of 15.26 × 15.26 m corresponding to the sample plot size of 232.9 m^2 was generated by means of GIS. The responses in question were predicted for all sub plots by means of the derived stratum specific models and statistics derived from laser pulse distributions from each plot, corresponding to those of the sample plots. Estimates for each validation plot (0.37 ha) were computed as mean values of the individual sub plot estimates. The difference between the estimated values $(\hat{Y})$ and the corresponding ground-truth (Y) were evaluated. For both model estimation methods, $\overline{D}$ express the prediction error individually for each response and is given by:

$$\overline{D} = \frac{1}{n}\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right) \quad (6)$$

with the corresponding standard deviation (SD):

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(D_i - \overline{D})^2} \quad (7)$$

The statistical significance of the mean differences was tested by means of t-test. A difference significant different from zero implies that a systematic error has occurred.

RESULTS

The preliminary PCA indicated a grouping of the X-scores according to strata. This means that plots from different strata influenced the principal components in different directions. Thus, stratum-specific PLSR models were estimated. Stratum specification is also in accordance with the OLS models. Furthermore the PCA indicated that hL, hdom, G and V constituted a group according to their Y-loadings. This means that these four variables spanned the Y-space in the same directions, which consequently implied that they were to be modelled together. Apprised by their Y-loadings, dg and N were not similar to hL, hdom, G or V, nor did they form a group of their own. Nevertheless, appraised by prediction error it was advantageous to model them as a pair. Last, the preliminary analysis indicated that estimation on logarithmic transformed data gave smaller prediction error. Hence, a transformation of all the variables was conducted.

Final PLSR models for mean height (hL), dominant height (hdom), mean diameter (dg), number of stems (N), basal area (G) and timber volume (V) were then estimated for the individual stratum. Table 2 displays dependent variables, number of components and explained variance for each model estimation. Note that there actually are as many PLSR models as there are dependent variables × strata (=12). As the table shows, the explained variance ranges over a large interval around approx. 70 %.

Table 2: Dependent variables, number of components and explained variance for the stratum specific PLSR model estimations.

Estimation #	Stratum	Dep. variables	# Components	Explained variance (%)
1	1	d_g, N	2	65.65
2	1	h_L, h_{dom}, G, V	1	75.10
3	2	d_g, N	2	57.04
4	2	h_L, h_{dom}, G, V	2	73.22

Table 3 displays validation results for the PLSR models and a comparison with OLS. We can observe that six mean prediction errors are smaller using PLSR, but that the OLS models in general yield smaller standard deviations. The OLS- and PLSR models have ten and six differences significantly different from zero, respectively.

Table 3. Differences $(\overline{D})^a$ between predicted mean values and observed mean for the validation plots of mean height (h_L), dominant height (h_{dom}), mean diameter (d_g), number of stems (N), basal area (G) and timber volume (V), respectively, and standard deviations (S.D.) for the differences using PLSR.

		PLSR		Comparison[b]	
Variable	Observed mean	$(\overline{D})$	S.D.	$(\overline{D})$	S.D.
Stratum 1. Poor site quality: n=19					
h_L (m)	15.57	-0.85**	1.14	OLS	OLS
h_{dom} (m)	17.65	-1.52***	1.58	OLS	OLS
d_g (cm)	20.32	0.14ns	1.05	PLSR	PLSR
N (ha^{-1})	680	-16ns	122	PLSR	OLS
G (m^2ha^{-1})	21.11	-1.21ns	3.91	PLSR	OLS
V (m^3ha^{-1})	162.3	-15.6ns	33.6	OLS	OLS
Stratum 2. Good site quality: n=19					
h_L (m)	20.27	-0.89***	0.81	OLS	OLS
h_{dom} (m)	22.94	-1.26***	0.71	OLS	PLSR
d_g (cm)	22.58	0.44ns	1.50	OLS	OLS
N (ha^{-1})	779	6ns	139	PLSR	OLS
G (m^2ha^{-1})	29.78	1.73ns	5.99	PLSR	OLS
V (m^3ha^{-1})	286.6	11.2ns	56.8	PLSR	OLS

a) Level of significance: ns=not significant. *=<0.05. **=<0.01. ***=<0.001.

b) The method that gives the best validation results is indicated by PLSR or OLS.

CONCLUSIONS

The preliminary PCA and -regressions gave valuable information of how to develop best possible models for the dependent variables in question. When disregarding this information and developing models using only prior knowledge, the prediction errors were increased. Hence, the selection of dependent variables modelled together, the stratification, and determination of number of components is regarded to be expedient.

It is previously pointed out that the laser data has a high level of collinearity and consequently only a few of the potential regressors can be utilized in the OLS models. This suggests that PLS regression potentially is a technique that can account for more of the relevant variance from the regressors. In this particular study, however, the results from the validation are ambiguous. Indeed, some of the comparisons in table 3 indicate that PLSR prediction is closer to the observed values than the OLS predictions, but the improvements are, however, small and the standard deviations are in general larger. The reasons for this are not evident. Foremost, it is probably due to that the variables selected by the stepwise regression procedure contain almost all the relevant variance. The potential advantages of using PLSR are consequently reduced.

Finally, this study indicates that PLSR is a statistical technique that can be suitable for modelling on laser data. Still, the results are not as uplifting as expected prior to the study. It is however, necessary to do further work using PLSR on laser data before final conclusions are made.

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DETERMINATION OF TREE SIZE DISTRIBUTION MODELS IN MATURE FOREST FROM LASER SCANNER DATA

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ABSTRACT

The aim of this study was to assess the accuracy of basal area distributions of sample plots in mature coniferous forest derived from small-footprint airborne laser scanner data. Regression analysis was used to relate a system of 10 percentiles defined across the range of observed diameters to various canopy height and canopy density metrics derived from the laser data. The method seemed to be robust with respect to bias and accuracy when mean height, stem number, basal area and volume at stand level as derived from predicted tree size distributions were used as validation criteria.

INTRODUCTION

The empirical tree size distribution is seldom measured over large areas for forest management and planning purposes. However, the use of tree-specific models in growth simulators requires that the tree size distribution is known or can be predicted. Quantifying the tree size distribution is valuable for economic purposes, for example when decisions on thinning are made (Hyink and Moser 1983). However, tree size distributions may also be used for analysing the structure of a forest in relation to forest biodiversity (e.g., Uuttera and Maltamo 1995, Kuuluvainen *et al.* 1996).

The basic tree distribution is usually the diameter distribution (Gove and Patil 1998). In order to give more weight to the large and more valuable trees diameter distributions weighted by basal area are sometimes used (Päivinen 1980, Deusen 1986). The diameter distribution or the basal area distribution can be constructed by assuming that it corresponds to some probability density function. However, a satisfactory characterization of the diameter distribution need not require a prior mathematical probability distribution. Borders *et al.* (1987) developed a percentile based diameter prediction method with a system of percentiles defined across the range of observed diameters.

Photogrammetric methods and photointerpretation have become important tools to quantify the timber resources. However, data required for derivation of tree size distributions at stand level can hardly be acquired by photointerpretation. During the last 10-15 years, several experiments have been carried out in order to determine various tree height metrics, mean stem diameter, stem number, basal area, and timber volume by different airborne laser profiling and scanning systems.

Thus, the objective of this study was to assess the accuracy of basal area distributions of mature coniferous forest derived from laser scanner data. A Method based on a system of percentiles defined across the range of observed diameters without assuming an a priori mathematical probability distribution was used. The method was evaluated in independent sample stands. In the present study, stratification according to site quality was used.

MATERIAL AND METHODS

Study areas

Forest areas in the municipalities of Krødsherad (60°10'N 9°35'E, 130-660 m a.s.l) (Site 1) and Våler (59°30'N, 10°55'E, 70-120 m a.s.l.) (Site 2), southeast Norway, were selected for the trial. As parts of large-scale practical forest inventories going on in the districts, the stand boundaries of all forest stands in the study areas were delineated by means of stereoscopic photointerpretation. The stands were classified according to criteria such as age class, site index, and tree species.

Two different types of ground-truth datasets were acquired in this study, i.e., (1) one consisting of sample plots distributed systematically throughout the entire study areas used to establish relationships between tree size distributions and laser data and (2) datasets with selected stands for which tree size distributions were employed to verify the performance of the developed models.

Estimation dataset

The study comprised 70 plots from site 1 (Krødsherad) and 83 plots from site 2 (Vaaler). All plots were located in mature forest. The plots in site 1 had an area of 233 m^2 and the plots in site 2 had an area of 200 m^2.

The plots were divided into two strata according to site index (Table 1). The first stratum consisted of 71 plots classified as mature forest with poor site quality. Poor site quality was assigned to sites with interpreted H_{40} site index values equal to or less than 11. The H_{40} site index is defined by average age at breast height and the average height of the 100 largest trees per hectare according to diameter at breast height (dominant height). The specific values of the H_{40} index relate to the dominant height at an index age of 40 years (Tveite 1977, Braastad 1980). Scots pine was the dominating tree species of the 71 plots. Finally, 82 plots were classified as mature forest with good site quality, i.e., interpreted H_{40} site index values greater than 11. The 82 plots were covered mainly by spruce.

Table 1: Summary of plot data.

Characteristic	Range			Mean
Stratum 1, Mature forest, poor site quality				
Number of plots				71
D_{min} (cm)	5	-	29	12.6
D_{max} (cm)	19	-	51	33.1
D_{max}-D_{min} (cm)	6	-	40	20.5
h_L (m)	9.9	-	23.3	15.7
N (ha^{-1})	150	-	1632	586
G (m^2 ha^{-1})	5.6	-	42.5	21.7
V (m^3ha^{-1})	29.7	-	430.5	168.6
Age (year)	35	-	171	103.8
Stratum 2, Mature forest, good site quality				
Number of plots				82
D_{min} (cm)	11	-	23	12.1
D_{max} (cm)	25	-	55	37.0
D_{max}-D_{min} (cm)	12	-	44	24.8
h_L (m)	12.9	-	26.1	20.2
N (ha^{-1})	200	-	2050	745.6
G (m^2 ha^{-1})	7.9	-	57.1	30.1
V (m^3ha^{-1})	56.6	-	678.0	296.6
Age (year)	29	-	152	78.1

d_{min} = minimum diameter, d_{max} = maximum diameter, h_L = Lorey's mean height, N= stem number, G= basal area, V = volume.

Within each plot, all trees with diameter at breast height d_{bh}>10 cm were callipered. The d_{bh} was recorded in 2 cm classes. The heights of sample trees selected with probability proportional to stem basal area at breast height were measured by a Vertex hypsometer.

The empirical discrete diameter distribution of each plot was derived as the sum of number of callipered trees within each diameter class using a class width of 2 cm. Accordingly, the corresponding empirical basal area distributions were derived by multiplying the stem number of each diameter class by the mean stem basal area of the individual diameter classes. Total stem number was computed as number of trees per hectare (*N*). Accordingly, stand basal area (*G*) was computed as basal area per hectare of the callipered trees. The mean height of each diameter class was computed from the sample trees, and volume of each diameter class was calculated from standard volume equations for individual trees. Finally, total plot volume (*V*) was calculated as the sum of the total volume of each diameter class. A summary of the field data is displayed in Table 1.

Validation dataset

The study comprised a total of 38 stands/plots from site 1 (0.4 ha) and 39 stands from site 2 (0.7-11.7 ha). They were selected subjectively among the stands delineated by practical forest inventory. All trees were callipered on site 1 and all trees in circular sample plots (100-200 m^2) distributed systematically according to a regular grid within each stand in site 2. Tree heights were measured on sample trees. A regular grid cell size corresponding to the sample size of 223 m^2 was generated for each stand.

Laser scanner data

A Piper PA31-310 aircraft carried the ALTM 1210 laser scanning system produced by Optech, Canada. In site 1 the laser scanner data were acquired in the period between 23 July and 1 August 2001 and in site 2 the data were acquired 8 and 9 June 1999 (leaf-on canopy conditions). First and last returns were recorded.

Methods

Estimation of basal area distributions derived from laser data involved the following two steps:

1. Derivation from discrete distributions based on field data of 10 sample percentiles forming a system of percentiles defined across the range of observed diameters.
2. Estimating a system of regression equations relating the 10 sample percentiles and stand basal area (G) to variables derived from the laser data.

Furthermore, the validation comprised steps 3-7:

3. Prediction of the 10 percentiles and G from the laser data according to the estimated regressions in step (2).

Regression analysis was used to create stratum-specific relationships between percentiles and basal area (G), respectively, as dependent variables and laser-derived metrics as independent variables. First and last pulse height distributions were created from the laser canopy heights (>2 m, see above) of each plot. A large number of statistics were derived from these distributions, and according to previous experiences (cf. Næsset 2002) they included mean values, coefficients of variation, and percentiles of the heights for 0%, 10%, …., 90%. Furthermore, several measures of canopy density were derived. The range between the lowest laser canopy height (>2 m) and the maximum canopy height as derived from the first pulse canopy height distribution, was divided into 10 fractions of equal length. Canopy densities were then computed as the proportions of first pulse laser hits above fraction # 0 (>2 m), 1, …, 9 to total number of first pulses. Corresponding densities were computed for the last pulse data as well.

In the regression analysis, multiplicative models were estimated as linear regressions in the logarithmic variables because such models were found to be suitable by others for estimation of diameter distribution percentiles from field data (Maltamo 1997) and G from laser data (Næsset 2002). Multiplicative models also ensure positive values of predicted percentiles. The multiplicative model was formulated as

$$Y = \beta_0 h_{0f}^{\beta_1} h_{10f}^{\beta_2} \cdots h_{90f}^{\beta_{10}} h_{0l}^{\beta_{11}} h_{10l}^{\beta_{12}} \cdots h_{90l}^{\beta_{20}} h_{\text{meanf}}^{\beta_{21}} h_{\text{meanl}}^{\beta_{22}} \times h_{\text{cvf}}^{\beta_{23}} h_{\text{cvl}}^{\beta_{24}} d_{0f}^{\beta_{25}} d_{1f}^{\beta_{26}} \cdots d_{9f}^{\beta_{34}} d_{0l}^{\beta_{35}} d_{1l}^{\beta_{36}} \cdots d_{9l}^{\beta_{44}} \quad (1)$$

whereas the linear form used in the estimation was

$$\begin{aligned} \ln Y = {} & \ln\beta_0 + \beta_1 \ln h_{0f} + \beta_2 \ln h_{10f} + \ldots + \beta_{10} \ln h_{90f} \\ & + \beta_{11} \ln h_{0l} + \beta_{12} \ln h_{10l} + \ldots + \beta_{20} \ln h_{90l} \\ & + \beta_{21} \ln h_{\text{meanf}} + \beta_{22} \ln h_{\text{meanl}} + \beta_{23} \ln h_{\text{cvf}} + \beta_{24} \ln h_{\text{cvl}} \\ & + \beta_{25} \ln d_{0f} + \beta_{26} \ln d_{1f} + \ldots + \beta_{34} \ln d_{9f} \\ & + \beta_{35} \ln d_{0l} + \beta_{36} \ln d_{1l} + \ldots + \beta_{44} \ln d_{9l} \end{aligned} \quad (2)$$

where $Y = G$ (m^2ha^{-1}) and values of the percentiles d_{10}, d_{20}, ..., d_{100} derived from field values of the basal area distributions for 10%, 20%, ..., 100% (cm); h_{0f}, h_{10f}, ..., h_{90f} = percentiles of the first pulse laser canopy heights for 0%, 10%, ..., 90% (m); h_{0l}, h_{10l}, ..., h_{90l} = percentiles of the last pulse laser canopy heights for 0%, 10%, ..., 90% (m); h_{meanf}, h_{meanl} = mean of the first and last pulse laser canopy heights (m); h_{cvf}, h_{cvl} = coefficient of variation of the first and last pulse laser canopy heights (%); d_{0f}, d_{1f}, ..., d_{9f} = canopy densities corresponding to the proportions of first pulse laser hits above fraction # 0, 1, ..., 9 to total number of first pulses; d_{0l}, d_{1l}, ..., d_{9l} = canopy densities corresponding to the proportions of last pulse laser hits above fraction # 0, 1, ..., 9 to total number of last pulses.

First, preliminary regression models were estimated by stepwise variable selection using the least-squares method (Anon. 1999). Individual equations were estimated for each of the dependent variables and no predictor variable was left in the models with a partial *F* statistics with a significance level greater than 0.05.

Second, a system of equations was estimated according to the seemingly unrelated regression (SUR) method (Zellner 1962, Anon. 1999). The system was estimated for the 10 percentiles, and it comprised 11 equations with d_{10}, d_{20}, ..., d_{100} and *G* as dependent variables. Each equation was specified in accordance with the preliminary stepwise variable selection. All independent variables were statistically significant at the 5% level in the SUR estimation. These equations were considered as final models. The final models were converted back to original scale by adding half of the variance to the intercept before conversion (cf. Goldberger 1968).

4. Derivation of the relative basal area in each diameter class according to the cumulative distributions defined by the predicted 10 percentiles in step (3).

The relative basal area in each diameter class was derived from the predicted values (step 3) according to the cumulative distributions. For the method based on a system of 10 percentiles, the 0% percentile was fixed to the truncation point (10 cm). The calculation of the frequencies in the respective diameter classes was based on the assumption that trees were uniformly distributed between adjacent percentiles (Borders *et al.* 1987). In order to produce a monotone distribution function and non-negative frequencies, predicted diameters at different percentiles are required to be in increasing order ($d_0 < d_{10} < \ldots < d_{100}$). This was obtained by adjusting non-increasing percentiles to the mean value of the preceding percentile and the percentile in question.

5. Derivation of number of trees in each diameter class by scaling the relative basal area in step (4) by stand basal area (*G*).

The total number of trees in each diameter class was found by scaling the relative basal area to *G* predicted from the laser data. Only diameters above the truncation point were considered.

6. Stand estimates were computed as weighted mean values of the individual cell estimates of the diameter distribution.
7. Predicted h_L, N, G and V and various measures of deviations between the predicted distributions and diameters recorded in field were used as validation criteria.

The validation was accomplished by comparing predicted variables as derived from the basal area distributions with observed values from the field inventory.

Finally, the predicted tree size distributions were evaluated by an error index proposed by Reynolds *et al.* (1988). The error index e was computed as the sum of the absolute deviations of the predicted minus the observed number of trees in each diameter class relative to the total number of observed trees, i.e.,

$$e = \frac{\sum_{j=1}^{k} \left| n_{pj} - n_{oj} \right|}{N} 100 \qquad (3)$$

where n_{pj} and n_{oj} are the predicted and observed number of trees, respectively, in diameter class j, j=1, 2, ..., k, and N is the total number of trees according to the field inventory.

RESULTS

First, the d_{10}, d_{20}, ..., d_{100} percentiles were derived from the empirical distributions of field values of each sample plot. For each stratum, a system of equations was used to regress these field values against the predictor variables derived from the distributions of first and last return laser data classified as canopy hits. The system comprising d_{10}, d_{20}, ..., d_{100} and total basal area (G) as dependent variables.

All the selected models comprised less than five predictor variables, which were all statistically significant at the 5% level. Predictor variables derived from the first as well as the last pulse data were represented. The coefficient of determination (R^2) ranged between 0.23 and 0.90. The average R^2 value was 0.42. The root mean square error (RMSE) was <0.24 for all models.

The stratum specific models were used to predict the diameter distributions for each cell in the validation stand. The calculated average distribution was used to compute an error index, h_L, N, G and V for stratum 1 and 2, respectively.

The mean error index ranged between 34.6% and 105.5%. The error index tended to be somewhat smaller for the highly productive forest (stratum 2) (51.2%) compared to less productive forest (stratum 1) (58.9%).

The predicted values for h_L, N, G and V were compared with field data (Table 2). The comparison revealed that five of the eight computed mean differences (bias) were larger than what could be expected due to randomness. For h_L the bias was significant in site 1 but not in site 2. The mean differences were 1.5 and –0.4 m and the standard deviations (SD) were 1.1 and 1.7m for stratum 1 and 2, respectively.

For N the differences did not differ significantly from zero at 5% level. The bias was –9 trees ha^{-1} and –31 trees ha^{-1} in stratum 1 and 2, respectively. The SD was 117 for stratum 1 and 145 for stratum 2.

The ground-truth values for G and V were significantly overestimated with 1.56 and 1.94 m^2ha^{-1} and 26.0 and 11.8 m^3ha^{-1}, respectively. The SD ranged from 1.83 to 1.94 m^2ha^{-1} and from 16.3 to 33.5 m^3ha^{-1} for G and V, respectively.

Table 2: Differences (D) between predicted and ground-truth values of Lorey's mean height (h_L), stem number (N), basal area (G) and volume (V), respectively, and standard deviation (SD) for the differences in stand predictions for each stratum.

		Observed	*D*			
Variable	Stratum	mean	Range	Mean		S.D.
h_L	1	15.8	-0.7 - 4.5	1.5	***	1.1
	2	19.8	-4.8 - 2.7	-0.4	ns	1.7
N	1	629	-274 - 234	-9	ns	117
	2	818	-454 - 216	-31	ns	145
G	1	20.33	-2.12 - 5.17	1.56	***	1.83
	2	29.40	-7.66 - 8.08	1.94	***	3.32
V	1	156.2	-13.9 - 50.4	26.0	***	16.3
	2	278.1	-61.0 - 89.5	11.8	*	33.5

Significance level: ns = not significant (> 0.05); * <0.05; *** <0.001.

DISCUSSION

In this study a method for estimating basal area distributions from laser scanner data was tested. The method, a system of 10 percentiles defined across the range of observed diameters, seemed to be robust with respect to bias when hL, N, G and V as derived from predicted tree size distributions were used as validation criteria.

It is difficult to compare the results with previous research related to distribution models due to methodological differences. Prediction models for distribution parameters and percentiles have usually been derived from intensively field-measured variables such as mean diameter by basal area, basal area weighted median diameter, total stand basal area, total number of trees, and age (e.g., Maltamo 1997, Kangas and Maltamo 2000, Maltamo et al. 2000).

The laser is probably unable to register the presence of trees growing "in the shadows" of the larger trees. However, since laser measurements may be appropriate to depict organic matter also in the lower parts of tree canopies (Lefsky et al. 1999, Lefsky et al. 2002), laser data may represent a potential for derivation of tree size distributions in multistory stands as well. It should therefore be considered whether laser data could be used to model multi-modal tree size distributions.

CONCLUSIONS

To conclude, the present trial has indicated that tree size distributions of sample plots in mature coniferous forest may be derived from laser scanner data with a precision of predicted hL, N, G and V of 7%-9%, 18%-19% ,9%-11% and 10%-12%, respectively, provided that a proper stratification is accomplished. The laser data themselves are probably representing a potential for improved stratification.

Even though small sample plots with a size of 200 m^2 may be inappropriate for diameter distribution modelling, at least in forest stands with low tree density, averaging over a larger area will tend to reduce prediction errors.

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ECOLOGICAL APPLICATIONS OF AIRBORNE LASER SCANNER DATA: WOODLAND BIRD HABITAT MODELLING

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ABSTRACT

Airborne laser scanning (ALS) is a relatively recent technology and yet a wealth of research already exists for forestry applications. By contrast ecological applications of ALS data have been reported only infrequently, in spite of an equal opportunity to address fundamental research questions with the unique data collection capability that ALS offers. This paper focuses on the specific ecological issue of modelling bird habitat quality using ALS data of broadleaf woodland.

Vegetation structure is an important component of habitat quality. For woodland birds, mapping the three-dimensional complexity of their habitat by field survey can be a time-consuming and difficult task. ALS can supply information on vegetation structure at a landscape scale and with high sampling density. We use small-footprint ALS data and show that reproductive performance in Great Tits (*Parus major*) and Blue Tits (*Parus caeruleus*) can be predicted using a map of woodland height. Since both Great Tits and Blue Tits feed their young on tree-dwelling lepidopteran larvae, canopy structure influences habitat quality via effects on both food abundance and its availability to parent birds. During the unfavourable weather of 2001, the best foraging conditions for Blue Tits occurred where the canopy was tall and well-developed, but for Great Tits a shorter canopy with a more varied height profile was most favourable. However, food availability is also influenced by weather conditions, affecting both food abundance and the birds' foraging abilities. Other factors can also be influential such as population density, parental quality, and competition for nest sites and food. Thus we show that the same woodland structure represented different habitat quality for Great Tits under different weather conditions.

INTRODUCTION

Models of organism-habitat relationships relate surveyed variation in the abundance or demographic rates of organisms to variation in the presence or extent of habitat variables (Fielding and Haworth 1995; Guisan and Zimmermann 2000). The enumeration of such relationships can enable the prediction of animal distribution patterns or demography in response to land-use or environmental change (Cowley *et al.* 2000). This has clear conservation implications.

The key to the predictive ability of organism-habitat models is the incorporation of habitat variables that reflect directly the mechanism of habitat selection. For terrestrial birds vegetation structure is a key determinant of both nesting and foraging habitat quality and plays a major role in habitat selection across a wide range of types from grassland to forest (Fuller and Henderson 1992, Coppedge *et al.* 2001). Other factors can also be influential such as population density, parental quality, and competition for nest sites and food (Lack 1971, Minot 1981, Przybylo *et al.* 2001). In addition to nest site requirements, there are several ways in which vegetation structure can influence habitat selection by woodland birds (Beier and Drennan 1997). Structure may impede movement of foraging birds both physically (Brodmann *et al.* 1997) and behaviourally (Desrochers and Hannon 1997) and may influence foraging efficiency through effects on detectability and accessibility of food items (Moorcroft *et al.* 2002; Whittingham and Markland 2002).

Quantifying woodland structure in the field usually involves multiple measurements of features such as stem sizes and densities (James and Shugart 1970, Fuller and Henderson 1992), estimation of plant species composition and measurements of light penetration through the canopy (Chen and Cihlar 1995). Such field-based measurements of structure can be highly time consuming, limited by problems of access (both geographically and spatially within habitat patches) and can often only be applied on a relatively small scale (e.g. Mueller-Dombois and Ellenberg 1974). Remote sensing techniques have the potential to quantify habitat characteristics at a landscape scale and in three dimensions (Roughgarden *et al.* 1991, Hill *et al.* 2002). As a consequence, remote-sensed data have been used to investigate bird species distributions (Bellamy *et al.* 1998, Saveraid *et al.* 2001) and to model bird habitat characteristics (Imhoff *et al.* 1997, Osborne *et al.* 2001).

Airborne Laser Scanning (ALS) is a remote sensing technique, operating on a principle of Light Detection And Ranging (LiDAR) that supplies fine-grained information on vegetation structure at a woodland scale (Næsset 2002). ALS devices such as the Airborne Laser Terrain Mapper (ALTM) use a high-repetition pulse laser range-finder, a scanning mechanism, differential GPS, and an Inertial Measurement Unit to measure the elevation at points within a swath beneath the flight-path of an aircraft (Baltsavias 1999). When striking a non-solid surface, such as a tree crown, each incident laser pulse can penetrate to an extent dependent on the density of the structure and the angle of incidence (Lefsky *et al.* 2002). A series of laser pulse returns recorded over a wooded landscape can supply information on 'top-of-canopy' elevation, canopy penetrability (from which canopy density may be inferred) and the underlying terrain.

This paper reviews the results of woodland bird habitat modelling using ALS data for an area of broadleaf woodland in Cambridgeshire, UK. We present relationships between woodland structure and breeding success for Great Tits (*Paurs major*) and Blue Tits (*Parus caeruleus*) and show how these relationships are dynamic, varying with weather conditions.

FIELD SITE AND DATA COLLECTION

Monks Wood National Nature Reserve (N.N.R.) is a 157 ha broadleafed woodland in Cambridgeshire, eastern England, UK (Figure 1). Its elevation ranges from 6 m to 46 m, with a maximum slope angle of 14.5° (Steele and Welch, 1973). The main upper-storey tree species are Common Ash (*Fraxinus excelsior*), English Oak (*Quercus robur*), Field Maple (*Acer campestre*), Silver Birch (*Betula pendula*) plus smaller numbers of Aspen (*Populus tremula*) and Small-leaved Elm (*Ulmus minor* Mill.). Ash is the most common and widespread tree species in Monks Wood, followed by Oak and Field Maple. Field Maple and Silver Birch are found scattered throughout the wood, whilst Aspen and Small-leaved Elm are more localised on the wetter soils. The dominant shrub species making up the under-storey and woodland fringes are Hawthorn (*Crataegus spp.*), Common Hazel (*Corylus avellana*), Blackthorn (*Prunus spinosa*), Dogwood (*Cornus sanguinea*) and Wild Privet (*Ligustrum vulgare*) (Steele and Welch 1973, Massey and Welch 1993).

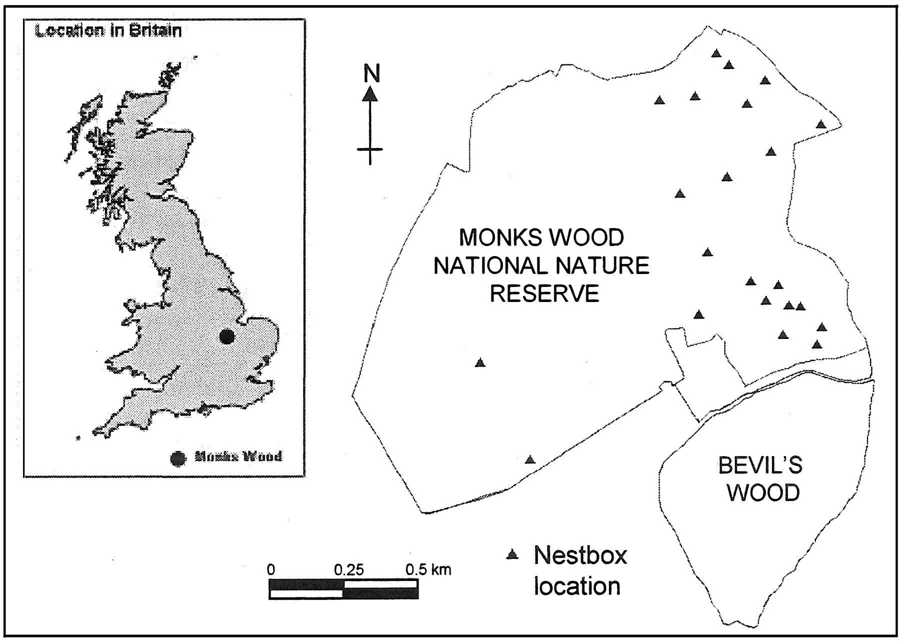

Figure 1: Monks Wood N.N.R. in Cambridgeshire, eastern England, UK (52°24' N, 0°14' W). The location of the 22 nestboxes are shown.

Monks Wood contains 22 nestboxes that can be occupied in any year by either Great Tits or Blue Tits (Figure 1). Being larger, Great Tits generally have the advantage in competition over nest holes and thus occupy a higher proportion of boxes each year than Blue Tits. The reproductive performance of Great Tits and Blue Tits has been recorded in these boxes for several years as part of a study of bird breeding success in relation to woodland habitat quality (Hinsley et al. 1999). Each year, nestlings are weighed using a spring balance on day 11 (day of hatching = 0) and mean weights, excluding runts, are calculated. The timing of breeding is recorded using first egg dates. Mean nestling body mass at 11 days of age will reflect territory quality (Przybylo et al 2001) because nestling mass combines the effects of food abundance with the adults' abilities to find it (foraging efficiency) and to deliver it to the nestlings (travel costs). Body mass of a nestling at fledging is an important predictor of its subsequent survival, fitness, and lifetime reproductive success (Naef-Daenzer *et al.* 2001).

ALS DATA ACQUISITION AND PROCESSING

An Airborne Laser Terrain Mapper (ALTM 1210, Optech Inc., Toronto, Canada) was flown over Monks Wood on 10 June 2000. Laser pulses were emitted by the ALTM with a wavelength of 1047 nm (near infrared). By scanning in sweeps perpendicular to the flight-line, the forward motion of the aircraft generated a saw-toothed pattern of point-sample elevation recordings. The parallel flight-lines had overlapping swaths, resulting in an irregular distribution of points. On average, 1 point was recorded every 4.83 m^2 across the study site. Both first- and last-return elevation data were recorded for each laser pulse, which generated a circular footprint on the Earth's surface with a diameter of approximately 0.25 m at nadir. The x- and y- position of each scanned point was supplied in British National Grid co-ordinates, whilst the z- position was supplied as elevation in metres above the Ordnance Survey of Great Britain 1936 Datum. The instrument precision at the flying altitude was approximately 0.60 m in x- and y-, and 0.15 m in z- (Baltsavias, 1999).

Continuous grid-based surfaces (i.e. Digital Surface Models: DSMs) were interpolated from the point-clouds of first-return and last-return elevation data. A Triangulated Irregular Network (TIN) was constructed for both the first- and last-return point-clouds, each based on a Delaunay triangulation of the point-sample elevation data. A rectangular grid of pixels was then extracted from each TIN using a linear interpolation method at a constant sampling interval of 1 m. This created a 1 m^2 spatial resolution raster DSM for both the ALS first- and last-return elevation data.

The underlying terrain of Monks Wood N.N.R. was modelled from the last-return ALS data. A process of morphological filtering was applied in which local elevation minima in the last-return DSM were identified. This was an adaptive filtering process in which the kernel size was varied in relation to heterogeneity in the last-return DSM. This enabled larger kernel sizes to be used for identifying local minima in areas of the woodland with few gaps or rides. The aim of this approach was to maximise the ability to extract a high proportion of the ground information from the last-return DSM without erroneously incorporating non-ground pixels. An analysis of the last-return DSM indicated that a kernel size of 60 x 60 pixels would be needed to guarantee that no non-ground data would be included in the extracted local minima. However, across Monks Wood N.N.R. where the canopy was more open (either due to gaps or rides) the kernel size could be reduced, potentially down to 15 x 15 pixels. Heterogeneity in the last return DSM was determined by calculating the standard deviation in focal 50 x 50 and 25 x 25 pixel kernels. Thresholds were then identified in these two standard deviation scores to determine for any part of the study site which one of five different sized kernels (between 60 x 60 and 20 x 20 pixels) was used to extract the local block minimum from the last-return DSM. The density of pixels extracted as 'ground data' thus varied across the study site. A Digital Terrain Model (DTM) was then generated by a thin-plate spline interpolation from the selected local elevation minima. This algorithm preserved the input elevation values of the extracted local minima and generated a 'smooth curve' surface between the data points.

A Digital Canopy Height Model (DCHM), supplying canopy height values in relation to the surrounding terrain, was then created by the per-pixel subtraction of the DTM from the first-return DSM. Both the DTM and DCHM had a 1 m^2 spatial resolution (Hill *et al.* 2002).

ORGANISM-HABITAT RELATIONSHIPS

The highest occupancy rate of nextboxes across Monks Wood occurred in 2001, when 19 of the 22 nestboxes were occupied; 11 by Great Tits and 8 by Blue Tits. Relationships were investigated for both species between nestling body mass at 11 days of age and canopy structure. These were presented in Hinsley *et al.* (2002). For Great Tits, mean nestling mass declined with mean canopy height (mean nestling mass = 21.40 – 0.26 canopy height, R^2 = 0.80, $P < 0.001$, n = 11). For Blue Tits, mean nestling mass increased with mean canopy height (mean nestling mass = 8.78 + 0.121 canopy height, R^2 = 0.61, P = 0.014 n = 8). These relationships are plotted in Figure 2. Mean canopy height was calculated from the ALS canopy height data for a sample area of 54 x 54 m (2916 pixels) centred on each occupied nestbox. Without knowing the actual foraging destinations of the birds, the sample area of 54 x 54 m was assumed to be representative of at least the core of each territory.

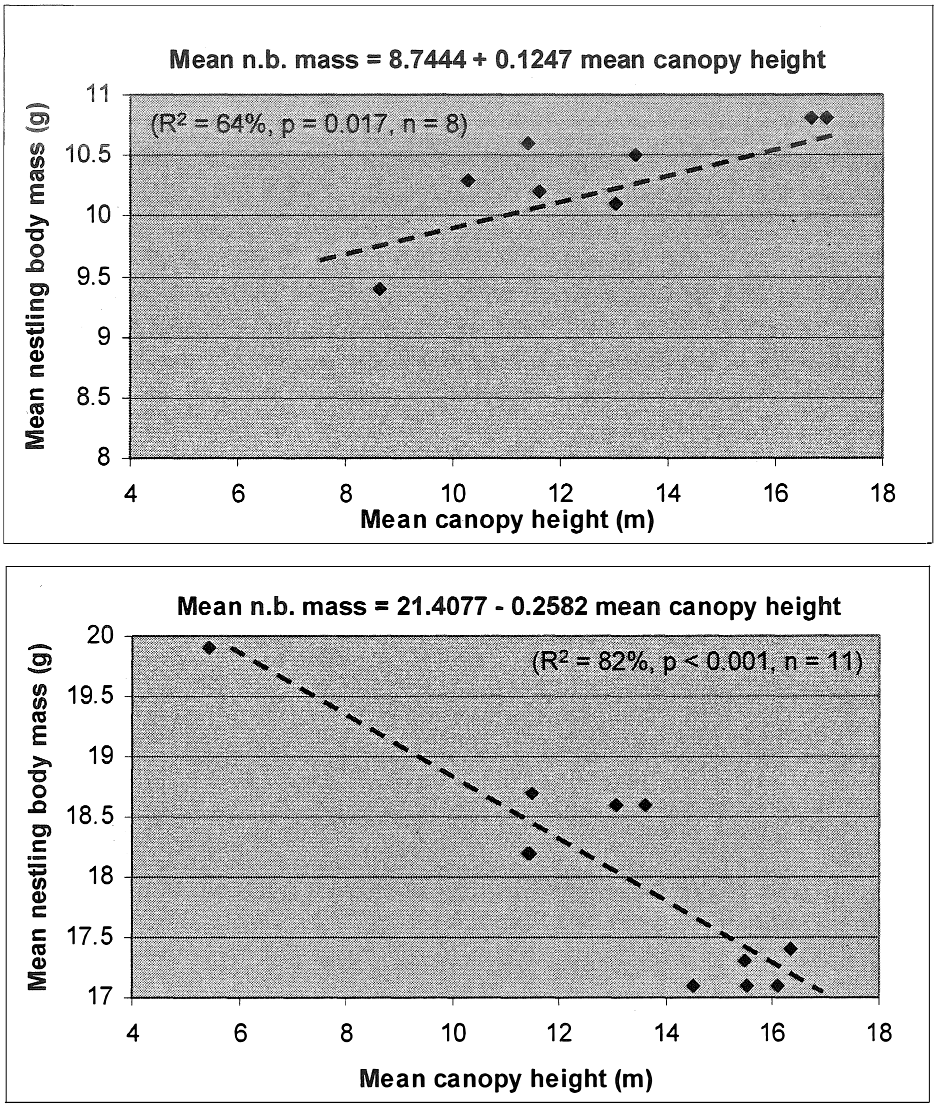

Figure 2: Scatterplot of mean canopy height against mean nestling body mass for Blue Tits (top) and Great Tits (bottom). The dashed line is the best-fit line plotted using the least-squares method.

The relationships between mean canopy height and mean nestling body mass were used to generate maps predicting nestling mass, and hence habitat quality, throughout Monks Wood NNR. This was demonstrated for Great Tits using the 2001 data by Hill *et al.* (2003). Mean canopy height in a 54 x 54 pixel kernel was calculated for each pixel of the DCHM and the regression equation was applied per pixel on the assumption that each pixel contained a nest site and was the centre of an uncontested territory. The standard error of prediction for the pixels containing the actual nestbox locations was ± 0.37 g (2.06% of average Great Tit nestling body mass). However, since there were insufficient nestboxes with which to both derive and test the regression equations, the standard error of ± 0.37 g over-estimated the predictive capacity of the model. In addition, the model generated a spurious, graded edge-effect because of the influence of areas of low canopy height beyond the boundary of the woods. Nonetheless, the potential to predict habitat quality, at both a high spatial resolution (i.e. 1 m^2) and on a woodland-scale, was clearly demonstrated.

The occupancy level of nestboxes in Monks Wood by Blue Tits in years other than 2001 was too low ($n \leq 6$) to enable the investigation of statistically robust organism-habitat relationships. For Great Tits, the nestbox occupancy level was higher and so the relationship between mean nestling body mass and mean canopy height has been investigated for the period 1997-2002. Studies of reproductive success in Great Tits typically show strong year effects in relation to environmental variables (Slagsvold 1976, Perrins 1979, Nager and van Noordwijk 1995). Weather conditions during breeding have considerable impact on success. According to McCLeery and Perrins (1998) an effective measure of spring weather in relation to conditions for breeding is the sum of the maximum temperature for each day from 1 March to 25 April (hereafter referred to as Σ max day temp). For the period of 1997-2002 a negative and highly significant relationship occurred between mean first date of egg-laying by Great Tits and Σ max day temp at Monks Wood (mean 1st egg date = 83.76 – 0.10 Σ max day temp, $R^2 = 0.97$, $P < 0.001$, $n = 6$) (Figure 3). In Figure 4, the r^2 for the relationship between mean nestling body mass and mean canopy height for each year of 1997-2002 is plotted against the Σ max day temp of each year. The Σ max day temp for the period of 1997-2002 had a range of 568-760 °C and a mean of 682 °C. For those years with a Σ max day temp below the 6 year mean, the relationship between mean nestling body mass and mean canopy height was negative and for those years with a Σ max day temp above the 6 year mean, the relationship between mean nestling body mass and mean canopy height was positive. However, only the years at the edge of the range of Σ max day temp values for the 6 year period produced statistically significant R^2 values at $P < 0.1$ (Table 1).

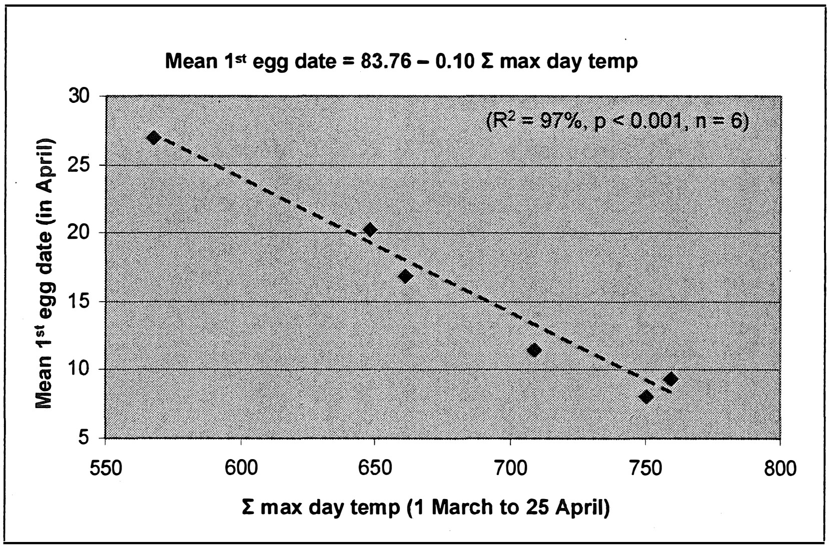

Figure 3: Scatterplot of mean first egg-lay date by Great Tits against Σ max day temp (1 March to 25 April). The dashed line is the best-fit line plotted using the least-squares method.

Table 1: Relationship between mean nestling body mass and mean canopy height for Great Tits in Monks Wood nestboxes for the period 1997-2002.

YEAR	R^2	P	n	Σ max day temp
1997	46	0.064	8	760
1998	8	0.412	11	661
1999	6	0.481	11	709
2000	16	0.288	9	648
2001	82	<0.001	11	568
2002	18	0.424	9	750

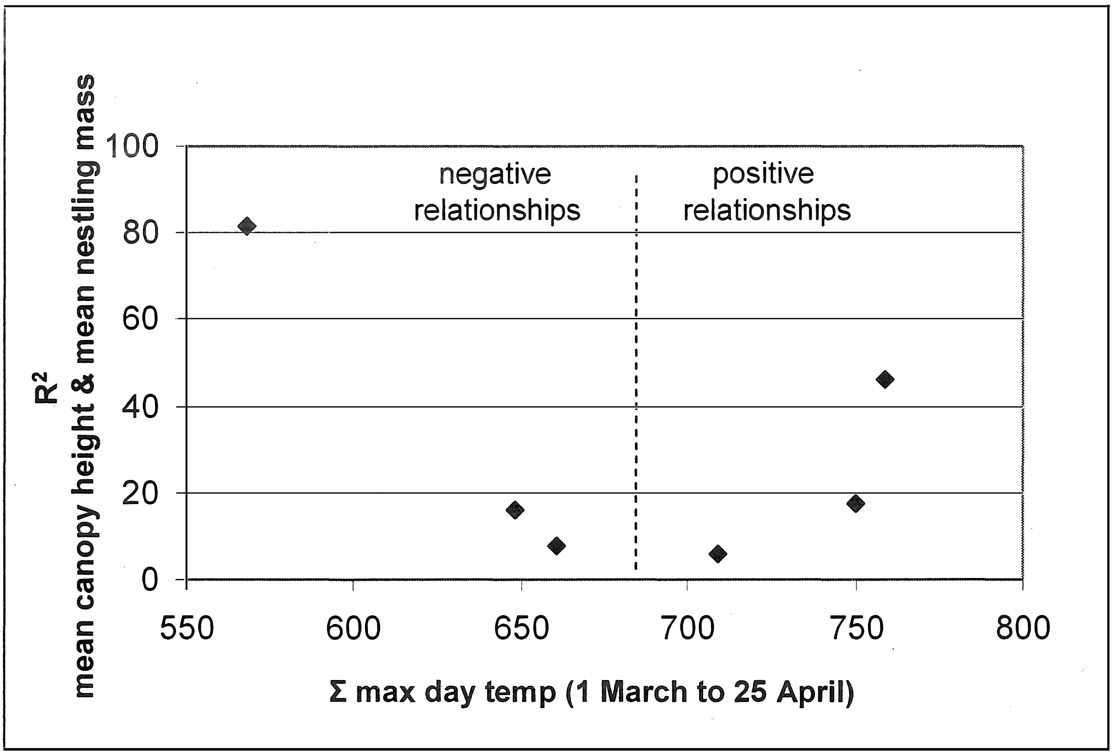

Figure 4: Scatterplot of the R^2 for the relationship between mean Great Tit nestling body mass and mean canopy height against Σ max day temp (1 March to 25 April). The dashed line is the mean value of Σ max day temp (682 °C) over the period 1997-2002.

DISCUSSION

The implication of the results for 2001 is that for Blue Tits the best foraging conditions were supplied by tall trees with a well-developed, closed canopy, whereas for Great Tits best foraging conditions were provided by a lower canopy with a more varied height profile. The difference in the relationship between nestling body mass and mean canopy height for Blue Tits and Great Tits probably relates to the two species' body masses and foraging behaviour (Hinsley *et al.* 2002). Blue Tits (9-11 g) concentrate their foraging in the outer parts of the tree canopy (Lack 1971), while Great Tits (17-20 g) tend to feed lower down, foraging more on larger branches and on the ground (Perrins 1979). Thus the structure provided by a tall, closed canopy, with most leaf growth concentrated in the top-canopy, may be more suitable for the smaller and more agile Blue Tit, whereas a more varied height profile may offer the larger Great Tit greater access to a sturdier vegetation structure and to the ground. In addition, the weather conditions during the breeding season of 2001 were poor (Balmer and Milne 2002). The optimum prey size for Blue Tits is smaller than that for Great Tits. The wet and windy conditions of spring 2001 may have had a disproportionate effect on the availability in tall canopy of the larger prey items taken by Great Tits. A lower and more varied canopy profile may provide more sheltered conditions for larger prey and thus better foraging success for Great Tits. Competition between the two species for prey might also be a factor; several studies have found that nestling weight in Great Tits is negatively correlated with Blue Tit population density (Minot 1981, Török & Tóth 1999).

The breeding season was relatively late in 2001 and, in general, late seasons are associated with poorer breeding performance (Hinsley et al. 1999). Under poor conditions for breeding, differences between both territory quality and parental performance might be expected to be most detectable in terms of their impact on nestling condition and survival. When we reported these results for 2001, we hypothesised that the assessment of territory quality may vary between years and such variation might account for the strong relationships between nestling body mass and vegetation height apparent for both Great Tits and Blue Tits in 2001 (Hinsley et al. 2002).

The results for Great Tits over the period 1997-2002 indicate that the physical structure of the woodland canopy that offers the best foraging varies with the weather. Under the poor weather of the 2001 breeding season, the best foraging conditions were afforded by a woodland canopy of relatively low mean height and varied structure. By contrast, 1997 was a warmer and drier spring and the best foraging conditions for Great Tits appear to have been provided by the taller, more developed canopy. A taller canopy, if associated with more mature trees, may have a greater leaf biomass and thus be likely to sustain a greater biomass of caterpillars. Thus, under the more favourable weather conditions of 1997 there was likely to have been a greater availability of prey caterpillars in tall canopy. In the years of the study period with intermediate spring weather conditions, there was no detectable competitive advantage for Great Tits in foraging either in the upper or lower canopy. In these years, woodland canopy structure had no detectable influence on breeding success via its influence on foraging, and instead we must look to different environmental variables and/or the role of individual bird quality and biotic interactions (e.g. inter- and intra-specific competition).

Vegetation structure data alone cannot, therefore, quantify or predict all of the habitat characteristics that determine quality for woodland birds. Surface reflectance data from airborne multi-spectral scanners such as the Compact Airborne Spectrographic Imager (CASI) or the Airborne Thematic Mapper (ATM) may also be useful in characterising woodland habitat. Reflected radiance in the visible and infra-red parts of the spectrum can supply a range of information including land-cover type, plant species composition, biomass and plant vigour (Curran 1980, Rock *et al.* 1986, Gerylo *et al.* 1998). The integration of ALS and multi-spectral data can enable the mapping of thematic classes that combine plant species and canopy structure information (Hill *et al.* 2002, Hudak *et al.* 2002). This may provide a spatial framework within which bird species distribution, abundances and productivity can be predicted. In addition, integrated remote-sensed data can supply the spatial information on habitat characteristics used as input in the technique of Ecological Niche Factor Analysis (ENFA) for modelling woodland, and other, habitat. In this procedure a number of eco-geographical variables are transformed into a set of partial niche coefficients (using pre-defined niche functions) and the weighted average provides a habitat quality index (Hirzel *et al.* 2001). A trial of this approach for Great Tit habitat modelling at Monks Wood N.N.R. used the eco-geographical variables: percentage of canopy gaps, percentage of oak/ash composing the canopy, distance to woodland edge and canopy height; all of which were retrieved from remote-sensed data (Balzter *et al.* 2002).

CONCLUSIONS

The use of ALS data for organism-habitat modelling is particularly apposite for woodland where the three-dimensional complexity of the habitat limits both the resolution and extent of field-based data collection. The example presented in this paper uses a measure of breeding performance (i.e. nestling body mass) to quantify organism-habitat relationships and predict habitat quality. However, the method is equally suitable for investigating species distributions in relation to habitat structure.

Vegetation structure is a key determinant of both nesting and foraging habitat quality for terrestrial birds. Both Blue Tits and Great Tits are woodland species that feed their nestlings principally on tree-dwelling lepidopteran larvae (Perrins 1979), the availability and distribution of which are likely to be influenced by canopy structure. However, food availability is also influenced by weather conditions, affecting both food abundance and the birds' foraging abilities. Other factors can also be influential such as population density, parental quality, and competition for nest sites and food. During the unfavourable weather of 2001, the best foraging conditions for Blue Tits occurred where the canopy was tall and well-developed, but for Great Tits a shorter canopy with a more varied height profile was most favourable. However, we have shown that the same woodland structure represented different habitat quality for Great Tits under different weather conditions.

The habitat data derived from ALS could be supplemented using multi-spectral or hyper-spectral data acquired from airborne scanners, and this can provide input to more advanced spatial organism-habitat modelling approaches such as ENFA. Following future acquisition of both remote-sensed data (ALS and multi-spectral) and bird census data for a number of woods in lowland Britain, we shall construct and test habitat quality maps to relate species distributions, abundances and patterns of persistence to habitat structure and composition. This will enhance our ability to identify important areas for management and to predict patterns of species persistence or loss resulting from changing environmental pressures in the UK and elsewhere.

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WOOD MICE AND STAND STRUCTURE USING HELICOPTER-BORNE LASER SCANNER

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ABSTRACT

We investigated that the effects of season and forest type on the numbers of wood mice captured, and the relationships between the numbers of wood mice captured in the plantation and independent factors as the distance from evergreen broad-leaved forest, LAI and the slope degree by applying lidar remote sensing technique in the Shikoku Region, Japan. For *Apodemus speciosus*, the numbers of individuals captured were significantly affected by the forest type, but not by the season. The numbers of individuals captured in the evergreen broad-leaved forest were significantly more than those in the plantation in fall and spring. For *A. argenteus*, the numbers of individuals captured were significantly affected by the forest type, but not by the season, and a significant interaction was detected between the two factors. In spring that *Quercus* did not bear acorns, the numbers of individuals captured in the plantation were significantly more than those in the evergreen broad-leaved forest. For *A. speciosus*, the numbers of individuals captured were significantly, negatively correlated with all factors in fall and spring. The standardized partial regression coefficients for the distance from the evergreen broad-leaved forest and the slope degree were lower than that for LAI. For *A. argenteus*, the multiple regression models were not fitted significantly. Consequently, the steep slope would limit the range of movement of *A. speciosus*, but not *A. argenteus*. *A. argenteus* would be a great seed disperser that carries *Quercus* acorns in to a long distance rather than *A. speciosus* in the plantation with the steep slope.

INTRODUCTION

The increase of timber demand for reconstruction after World War II caused conversion from natural forest to sugi (*Cryptomeria japonica*) and hinoki cypress (*Chamaecyparis obtuse*) plantations in Japan. The rate of plantation was very high in Shikoku region. The evergreen broad-leaved forest with small area was scattered in the plantation. At present, the abandoned plantation is increasing. It is demanded that the recover from the plantation to the evergreen broad-leaved forest, however, little is known about succession in abandoned plantation. To understand about the recover of evergreen broad-leaved species in the plantation, it is important to investigate the dynamics of the dominant canopy species, *Quercus*, in particular, seed dispersal stage which is first process of recover. The plant species that bear acorn such as *Quercus* is synzoochory (Vander Wall, 1990). Wood mice, jay, and squirrel disperse the acorns by scatter hoarding in transporting acorn (Vander Wall, 1990). Thus, it is need to investigate the density and behavior of seed disperser. In this study, we focus on wood mice. In Japan, *A. speciosus* and *A. argenteus* play seed dispersal role through their food hoarding behavior (Miyaki and Kikuzawa, 1988; Miguchi, 1994). Abundance and occurrence of wood mice relate to season, year (Miguchi, 1988; 1996) and forest structure, particularly 'canopy - under understory vegetation – topography' structure (Nishikata, 1981; Shioya *et al*., 1990; Sekijima, 1999; 2001).

Lidar remote sensing is very useful for forestry and ecology because of its three-dimensional information acquisition. One possibility of utilization of airborne lidar measurement is an application to forest inventory in order to reduce the cost of field survey as well as understand forest characteristics spatially (Næsset and Bjerknes, 2001; Lefsky *et al*., 2001; Næsset and Økland, 2002). Pervious studies showed that forest parameters such as tree heights, number of stems, and stand volume could be estimated accurately (Næsset, 1997; Nelson, 1997; Magunussen and Boudewyn, 1997; Magunussen *et al*., 1998; Means *et al*., 2000). Recently, individual tree attributes were also derived from airborne scanner data with high density of footprints on the ground (Hyyppä *et al.*, 2001; Persson *et al.*, 2002; Brandtberg *et al.*, 2003; Hirata *et al.*, in press). Application for ecological studies has been also tried (Lefsky *et al.*, 2002). So ecologists are now interested in lidar remote sensing technique to expand their process studies to spatial understandings (Hinsely *et al.*, 2002).

This study aims to investigate the occurrence of wood mice as seed disperser around a boundary between an evergreen broad-leaved forest and a plantation and to apply lidar remote sensing to the study of seed dispersal in rugged terrain. We address the following questions: (1) Do the season and the forest type affect the occurrence of wood mice? ; (2) Do the occurrence of wood mice in a plantation relate to the distance from an evergreen broad–leaved forest, the slope and LAI?

METHODS

Study area and plot establishment

The study plot was located in the Ichinomata national forest, Shikoku Region, Japan (33°09' N, 132°55' E, 430 –780m above sea level). 80% of the forest is artificial and the rest is natural forest in this area. Mean monthly temperature is 13.0°C, with the highest mean of 23.5°C in August and the lowest of 2.3°C in January. Annual precipitation is about 2900mm, concentrated from June to September and with little from November to March. Maximum snow depth is around 20cm, but it usually melts away in a few days. Dominant canopy species are *Quercus salicina*, *Quercus acuata*, *Querucus sessiliifolia*, *Catanopsis sieboldii*, *Cleyera japonica*, *Eurya japonica*, *Symplocos prunifolia* and *Illicium anisatum*. *Quercus* bear acorns in fall (October to December). The main species of plantation are sugi (*Cryptomeria japonica*) and hinoki cypress (*Chamaecyparis obtuse*).

The study plot was established ranging from an evergreen broad-leaved forest to a plantation of hinoki cypress. A laser range finder (LaserAce 300) was used to survey a 150 m *100 m (1.5 ha) sampling grid of 10 m intervals. A differential GPS (Pathfinder, Trimble) was used to determine the positions of four corners of the plot by the Japan-19 Plane Orthogonal coordinates system with the Tokyo datum. Geographic coordinates of each sampling grid were calculated from the coordinates of four corners to overlay results of helicopter-borne laser scanning. 100 m * 100 m of the plot is occupied by a plantation of hinoki cypress. The number of stems of hinoki cypress is 1500 in plot. And the rest is an evergreen broad-leaved forest. A ridge divides the plantation and the evergreen broad-leaved forest. This plot is characterized by steep slopes and rugged terrain.

Laser scanner data

Compared with general remote sensing such as satellite sensors, traditional aerial cameras and airborne multi-spectral sensors, airborne or helicopter-borne laser scanning is the expansion from two-dimensional space to three-dimensional one.

The laser scanner system transmits the laser pulse at 1064 nm (near-infrared) and receives the first and last echoes of each pulse. The elapsed time between transmittance and receipt is measured to calculate the distance between the system and the object. Laser scanner data were collected on 28 October 2002. The ALMAPS (Asahi Laser Mapping System), which consists of the ALTM 1225, the GPS airborne and ground receivers, and the IMU, was used to acquire the laser scanner data. The flight altitude of the helicopter above the ground was about 250 m and the average flight speed was approximately 13.9 m/sec. The pulse repetition frequency was 25 kHz and the scan frequency was 25 Hz. Maximum scan angle (off nadir) was 12°. The beam divergence was 1.0 mrad. Overlap of scanning between neighboring flight lines was about 40 %. Measurement density was 23.4 points/m^2. Therefore, the footprint diameter was approximately 25 cm and the distance between neighboring footprints was about 20 cm. Both first pulse and last pulse were acquired to recover the canopy structure and terrain conditions. Footprints were registered to geographic coordinates using Kinematic GPS after the flight. Post-processing for the laser scanner data was performed to correct aberration. A fine DEM of the study plot was produced using the last pulse data. A local minimum filter was used to remove the effect of canopy, stem, understory vegetation and other objects on the ground from the last pulse data (Hirata *et al*, 2003).

Wood Mice Trapping

We set 176 live traps on the intersection of 176 square grids of 10m intervals in the study plot and captured wood mice as seed disperser by using the mark-recapture methods in a fruiting and a non-fruiting season of *Quercus*. The trappings were conducted during eight nights in fall (October to November 2002) and spring (April 2003), respectively. We placed sweet potato and sunflower seeds as bait of wood mice into the traps every morning.

Data Analysis

We used two-way ANOVA tests and Tukey's multiple comparison tests to determine whether the numbers of captured wood mice are affected by the factors as follows: season (fall as fruiting season, spring as non-fruiting season of *Quercus*) and forest type (evergreen broad-leaved forest, the plantation). We performed those analyses by using wood mice data per 100 traps per day. Multiple regression analyses were used to determine the relationship between the numbers of captured wood mice and the distance from the evergreen broad-leaved forest, slope degree, and LAI. The slope degree of each trapping point was calculated from 1m DEM data. We performed the multiple regression analyses by using wood mice data that was pooled data during eight days at each trap in trapping period of fall and spring, respectively. We used SPSS Version 11.0 software (SPSS, Inc. 2001) for all statistical analysis.

RESULTS

DSM (digital surface model) and DEM (digital elevation model) for the study plot were generated from the fist pulse data and the last pulse data respectively (Figure 1). Figure 2 shows the difference between the DSM and the DEM, i.e., digital canopy height model (DCHM) with gray scale. This figure demonstrates that the trees in evergreen broad-leaved forest have large crown and the heights of hinoki cypress trees depend on the area, i. e. topography. From overlay of DCHM on DEM, it was found that the growth of trees along the valley was better than the growth along the ridge in the hinoki cypress forest. The differences of tree heights except suppressed trees between the LIDAR measurement and the field measurement were almost below 1 meter. Average tree heights are 12m along the ridge and 15m in valley side. We have to note that each crown height in DCHM is overestimated in valley side and underestimated in ridge side because of topography.

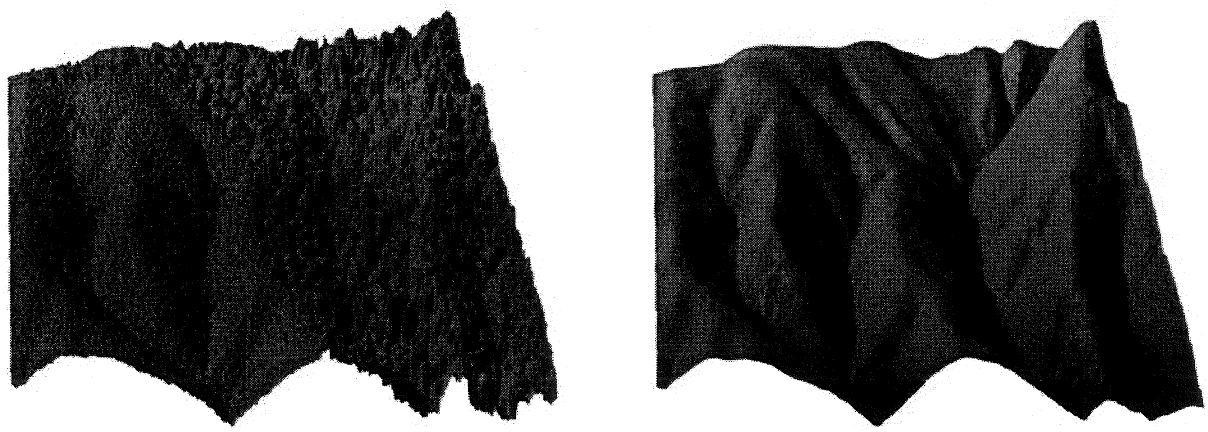

Figure 1: DSM from the first pulse data (left) and DEM (right) from the last pulse data.

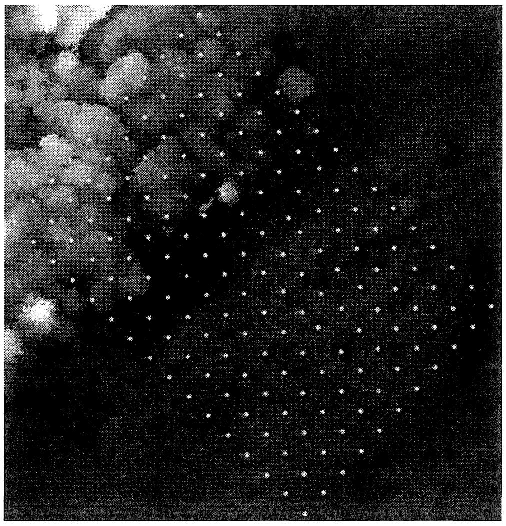

Figure 2 : DCHM from the difference between DSM and DEM (yellow points shows trapping points).

In total, 63 individuals and 94 individuals of two species (*A. speciosus* and *A. argenteus*) were captured during eight days in fall and spring, respectively.

For *A. speciosus*, the numbers of individuals captured were significantly affected by the forest type, but not by the season (Table 1a). The numbers of individuals captured in the evergreen broad-leaved forest were significantly more than those in the plantation in both fall and spring (Figure 3a). The difference in the numbers of individuals captured was not significant between fall and spring in the evergreen broad-leaved forest (Figure 3a).

For *A. argenteus*, the numbers of individuals captured were significantly affected by the forest type, but not by the season (Table 1b), and a significant interaction was detected between the season and the forest type. Thus, in fall that *Quercus* bore acorns, the difference in the numbers of individuals captured was not significant between the plantation and the evergreen broad-leaved forest (Figure 3b). In contrast, in spring that *Quercus* did not bear acorns, the numbers of individuals captured in the plantation were significantly more than those in the evergreen broad-leaved forest (Figure 3b). The difference in the numbers of individuals captured was not significant between fall and spring in the evergreen broad-leaved forest (Figure 3b).

For *A. speciosus*, the numbers of individuals captured were significantly, negatively correlated with all factors in fall and spring (Table 2a). The standardized partial regression coefficients for the distance from the evergreen broad-leaved forest and the slope degree were lower than that for LAI. However, the multiple coefficients of determination were lower remarkably (R^2=0.165, 0.244).

For *A. argenteus*, the multiple regression models were not fitted significantly (Table 2b).

Table 1: Two-way ANOVAs for the effects of season and forest type on the numbers of captured wood mice per 100 traps per day.

a) *Apodemus speciosus*

Source of variation	df	SS [1]	*F*	*P*
Intercept	1	135.30	93.04	< 0.0001
Season	1	2.09	1.44	0.241
Forest type	1	50.80	34.94	< 0.0001
Season × Forest type	1	0.03	0.02	0.896
Residual	28	40.72		

b) *Apodemus argenteus*

Source of variation	df	SS [1]	*F*	*P*
Intercept	1	410.41	120.8	< 0.0001
Season	1	12.45	3.664	0.066
Forest type	1	33.42	9.835	0.004
Season × Forest type	1	26.39	7.767	0.009
Residual	28	95.13		

1) Sum of squares

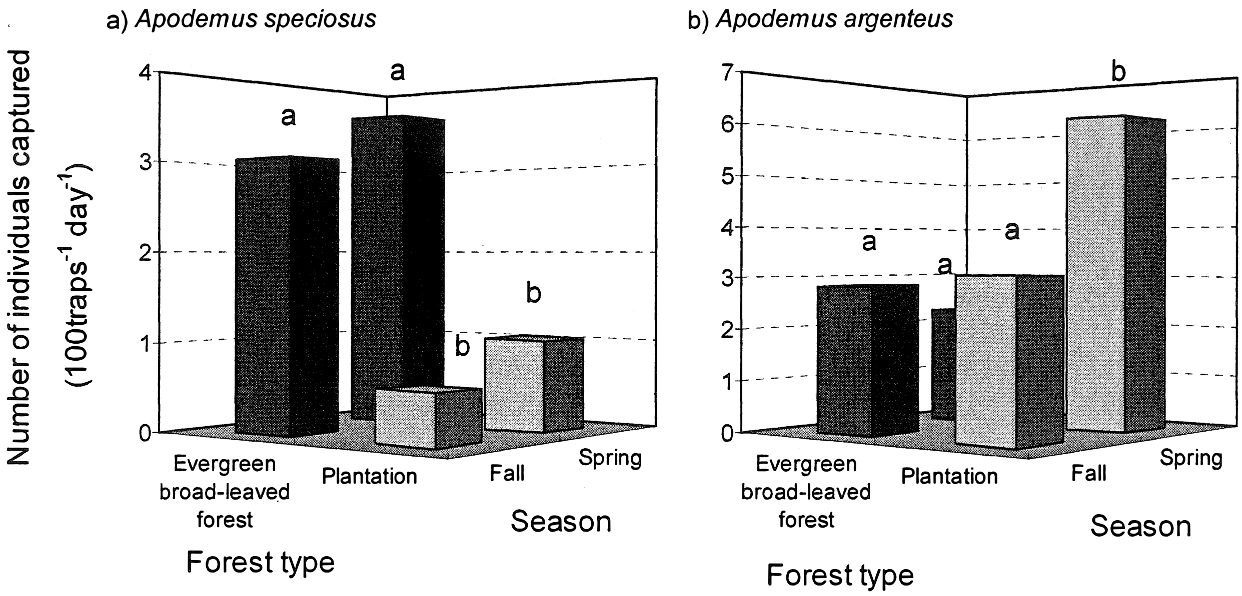

Figure 3: Comparisons of the numbers of captured individuals between fall and spring, and between the evergreen broad-leaved forest and the plantation. Fruiting and non-fruiting season are fall and spring, respectively. Bars are the means of 8 trappings per 100 traps per 8 days. Different letters in a figure show significant differences (P<0.05, Tukey's multiple comparison test).

Table 2: Multiple regression analyses of the relationships between the numbers of captured wood mice per trap per eight days in the plantation and independent factors as the distance from the evergreen broad-leaved forest, the slope degree and LAI in fall and spring.

a) *Apodemus speciosus*

Season	Dependent variable	R^2 1)	*P*	Independent variable	β 2)	*P*
Fall	Number of individuals captured	0.165	< 0.0001	Distance from evergreen broad-	-0.267	0.004
				Slope degree	-0.207	0.022
				LAI	-0.200	0.023
Spring	Number of individuals captured	0.244	< 0.0001	Distance from evergreen broad-	-0.298	0.001
				Slope degree	-0.303	0.001
				LAI	-0.179	0.031

b) *Apodemus argenteus*

Species	Dependent variable	R^2 1)	*P*	Independent variable	β 2)	*P*
Fall	Number of individuals captured	0.044	0.156	Distance from evergreen broad-	-0.021	ns
				Slope degree	-0.112	ns
				LAI	-0.180	ns
Spring	Number of individuals captured	0.045	0.148	Distance from evergreen broad-	-0.078	ns
				Slope degree	-0.149	ns
				LAI	0.072	ns

1) Multiple coefficient of determination
2) Standardized partial regression coefficient

DISCUSSION

On this study, we tested whether the occurrence of wood mice were related with the season (fall as fruiting season, spring as non-fruiting season *of Quercus*) and the forest type (evergreen broad-leaved forest, the plantation). The occurrence of *A. specios*us was significantly affected by the forest types, but not by the season. The numbers of individuals captured in the evergreen broad-leaved forest were significantly more than those in the plantation in both fall and spring. The difference in the numbers of individuals captured was not significant between fall and spring in the evergreen broad-leaved forest. Thus, this implies that *A. speciosus* intensively occurred in the evergreen broad-leaved forest, without being influenced by existence of *Quercus* acorns fallen on the ground.

On the other hand, the occurrence of *A. argenteus* was significantly affected by the forest type, but not by the season, and a significant interaction was detected between the two factors. In spring that *Quercus* did not bear acorns, the numbers of individuals captured in the plantation were significantly more than those in the evergreen broad-leaved forest. The difference in the numbers of individuals captured was not significant between fall and spring in the evergreen broad-leaved forest. Thus, this implies that *A. argenteus* did not occurred intensively in the evergreen broad-leaved forest in fall that *Quercus* acorns fallen on the ground.

In addition, we tested whether the occurrence of wood mice were related with the distance from evergreen broad-leaved forest, LAI, and the slope degree, whose data were obtained by lidar remote sensing. The occurrence of *A. speciosus* was significantly, negatively correlated with all factors. Thus, the numbers of *A. speciosus* increased with decreasing the distance from evergreen broad-leaved forest, the slope degree and the vegetation cover. For *A. argenteus*, there was no significant correlation.

We found that the occurrence patterns of *A. speciosus* and *A. agrenteus* differed, and also determined that the factors affected the occurrence patterns of them by using lidar remote sensing data: significant factors for *A. speciosus*, the forest type, the distance from evergreen broad-leaved forest, the slope degree and LAI; those for *A. argenteus*, the forest type and the season. Our results suggest the following behavior patterns of *A. speciosus* and *A. argenteus*. First, they were necessarily attracted *Quercus* acorn fallen on the ground in fall and therefore would not move intensively in the evergreen broad-leaved forest in fall, because the occurrence of them was not concentrated in the evergreen broad-leaved forest in fall. The population densities of the two species were sharply changed by the season and the year (Miguchi, 1988; Sekijima, 1999; 2001). Miguchi (1996) found that the population density of *A. argenteus* increased in spring after mast fruiting of beech, in contrast, it decreased in spring after not mast fruiting of beech in cool temperate beech forest of Japan. Thus, the production of *Quercus* acorn would affect the seasonal fluctuation of the population densities of the two species in the study plot. Second, *A. speciosus* would prefer the evergreen broad-leaved forest to the plantation and/or the range of movement of *A. speciosus* would be limited by the steep slope, because the occurrence of *A. speciosus* was concentrated in and near the evergreen broad-leaved forest. Third, *A. argenteus* prefer the plantation to the evergreen broad-leaved forest and/or the range of movement of *A. argenteus* would be limited by competition with *A. speciosus* in spring, because the occurrence of *A. argenteus* was concentrated in the plantation in spring. In previous studies, the difference in the microhabitat uses between the two species is caused by the difference in the development grade of understory vegetation and litter (Nishikata, 1981; Shioya *et al.*, 1990; Sekijima, 2001). Also, the microhabitat uses of the two species seasonally changed, and this would reflect their ecological characteristics and/or strength of competition (Sekijima, 1999). In this study, we focused on the slope degree that seldom focused in previous studies, and found that the microhabitat use of *A. speciosus* was affected by the slope degree. Therefore, *A. argenteus* would be a great seed disperser that carries *Quercus* acorns in to a long distance rather than *A. speciosus* in the plantation with the steep slope.

CONCLUSIONS

We found that the occurrence patterns of *A. speciosus* and *A. argenteus* differed, and also determined that the factors affected the occurrence patterns of them by using lidar remote sensing technique. The steep slope would limit the range of movement of *A. speciosus*, but not *A. argenteus*. *A. argenteus* would be a great seed disperser that carries *Quercus* acorns in to a long distance rather than *A. speciosus* in the plantation with the steep slope. Lidar remote sensing is very useful for ecological study.

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LASER SCANNING FOR IDENTIFICATION OF FOREST STRUCTURES IN THE BAVARIAN FOREST NATIONAL PARK

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ABSTRACT

In the year 2002 the project "Evaluation of remote sensing based Methods for the identification of forest structures" was started. During 2002 and 2003 an extensive dataset was collected on an area of 30 km^2 distributed over 4 test areas. There were airborne surveys with a laser scanner, a multifrequent radar system, two optical scanners and conventional color and color infrared aerial photography. On the ground tree data was collected on 44 reference sites and tree bole positions were determined with an accuracy of centimetres. In addition, data of 712 permanent sample plots of the forest inventory was collected.

To assess the height accuracy of tree measurements a digital crown model was derived from lidar data and 3055 trees larger then 5 meters in height were measured on the ground. Out of these 32.77 % could be clearly identified and were used for the comparison of the different measurement methods. The mean of the differences between ground measurements and the DCM was -0.53 m with a standard derivation of 1.24 m. The mean of the absolute differences was 1.01 m with a standard derivation of 0.90 m. To correct the underestimation of tree heights resulting from lidar data linear regression models have been developed. Different error sources were analysed and considered to be of minor relevance for forest applications. As a result, height determination on the basis of lidar data is as least as accurate as conventional ground measurements and is almost operational.

INTRODUCTION

The research described herein was conducted in the Bavarian Forest National Park which is located in south-eastern Germany along the border to the Czech Republic. Within the park three major forest types exist: montane spruce forests with Picea abies and partly Sorbus aucuparia above 1100 m; submontane mixed forest with Picea abies, Abies alba, Fagus sylvatica and Acer pseudoplatanus on the slopes between 600 and 1100 m; and spruce forests in wet depressions, often evidencing cold air ponds, in the valley bottoms. The montane spruce stands were severely affected by the spruce bark beetle (Ips typographus) in the 1990s.

In the year 2002 the Project "Evaluation of remote sensing based methods for the identification of forest structures" was initiated. New methodologies are necessary because data acquisition in the forests of the national park is challenging: the remoteness and the high proportion of dead wood makes data collection expensive and dangerous for the inventory staff. Moreover, the traditional methods of permanent inventory and forest structure mapping can not deliver continuous information about the horizontal forest texture, which is of high importance for conservation issues.

The aim, therefore, of the study is the evaluation of different remote sensing techniques and analysis methods for detecting and mapping forest structures (Table 1). In a further step, there are plans to develop special applications for the needs of the national park administration. Here the main task is to develop a semi-automated approach for the mapping of forest development stages.

Table 1: The research focus in the project is on the following forest structures

Single Tree	*Tree stand*
position	boundary
species	closure
height	layer structure
crown area	volume

The first period of the project which continued until June 2003 was characterised by data acquisition, preparation and data storage. Four test areas with an overall size of 30 km^2 were selected. Two of these test areas were established in the core zone of the National Park where the forests have been unmanaged since 1970. The two other sites were established in an area which was incorporated into the park in 1997. Here, commercial forestry took place until this time. The stratum of the first two test areas is considered as "natural forest" and the other one as "managed forest". The test areas within each stratum are distributed in such a way that they include examples of all three forest types.

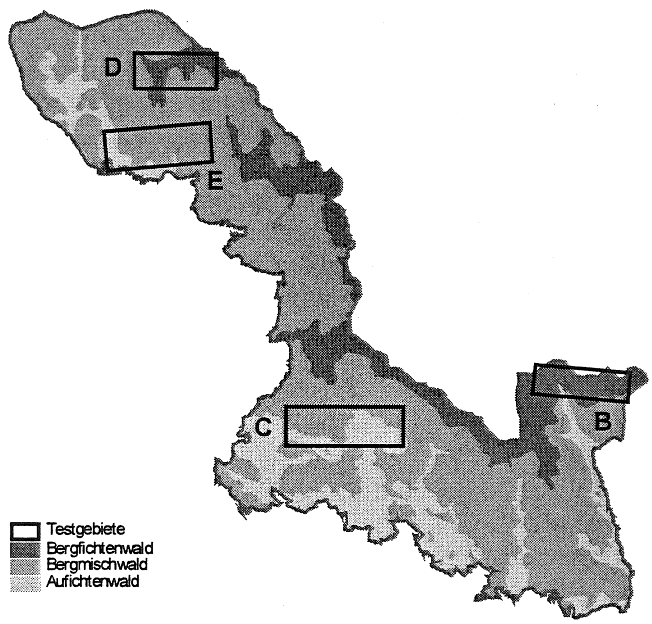

Figure 1: The different forest types in the Bavarian Forest National Park and the location of the Test areas. B and C are within the "natural forest" area, D and E are in the "managed forest" stratum. (Light grey: spruce forests of the valleys, medium grey: mixed mountain forests, dark grey: mountainous spruce forests).

Data that has been collected in the project

LIDAR

There were two flights with the "Falcon" airborne lidar system from TopoSys. The first flights were in March 2002 (valleys; C, E) and May 2002 (high elevations, B,D) after snowmelt but prior to foliation of the deciduous trees. Height measurements were acquired with a measurement density of 5/m^2. The second flight was on September 3rd 2002 and measurement density was 10/m^2 . For more details see Wehr and Lohr (1999).

Table 2: System parameters of the TopoSys laserscanner (TOPOSYS, 2003)

Sensor type	Pulsed fiber scanner
Range	< 1600 m
Wave length	1560 nm
Pulse lenght	5 nsec
Scan rate	653 Hz
Pulse repetition rate	83 000 Hz

Distance resolution	1,95 cm
Scan with	14,3°
Range	< 1600m
With (at max. range)	390m
Data recording	First Echo, Last Echo, Intensity
Average measurement density (at max. range)	3 meas./m^2

MULTIFREQUENT RADAR

A flight with the experimental SAR-System (E-SAR) from the German Aerospace Center was also flown on September 3 rd 2002, but data acquired covered only test area C. The settings of the radar system are described in Table 3.

Table 3: Frequencies and configurations during the E-SAR flight.

Frequency	*Polarisation*	*Interferometry*	*Spatial Baselines*	*Temporal Baselines*
P-Band	HH-HV-VH-VV	-	-	-
L-band	HH-HV-VH-VV	Repeat-Pass	0,5,10,15 (x2)	10 min.
C-band	HH-HV / VH-VV	-	-	-
X-band	VV	Single-Pass	1	-

AERIAL PHOTOS

In May 2002, after the snowmelt, color infrared aerial photographs (CIR AP) were acquired with a scale of 1:3500 in test area B. These photographs were scanned at 10 micrometers, resulting in a ground resolution of 0,035 m.

In October 2002, a second AP acquisition was made with a scale of 1:10000. These images covered the whole park and were scanned at 15 micrometers, resulting in a ground resolution of 0,15 m.

In addition, we had access to a relatively long time series of historical color infrared photographs. Since 1988 there have been flights every year in scales ranging from 1:5000 and 1:15000.

OPTICAL SCANNERS

Electro-optical images were acquired simultaneously to the lidar range measurement acquisition. Image data was recorded with the line camera of Toposys. The camera records four channels: B (440-490 nm), G (500-580 nm), R (580-660 nm) and NIR (770-890 nm). The ground resolution of these images is 0,5 meters.

Another optical data source was flown more recently. On June 30rd Z/I Imagings Digital Mapping Camera (DMC) was used to produce images with a ground resolution of 0,045 m in test area B and 0,2 to 0,3 m in the other areas. The system is equipped with four pan and four multispectral camera heads (red, green, blue and near infrared).

GROUND DATA

Between 2001 and 2002, 16 reference plots were established and 28 existing permanent research plots were measured within the vegetation period. The size of these reference plots ranges between 20 by 50 to 50 by 50 meters. In 30 reference plots every tree position was measured with an accuracy of centimetres, in 14 with an accuracy of decimetres. From each tree higher than five meters DBH, height and crown base were measured. On eight plots we also measured the crown size.

In 2002 a forest inventory was conducted in the test areas. Inventory sample points were distributed in a regular grid with an edge length of 200m. Each sample unit consists of a permanent inventory plot with concentric circles with graduated diameters in breast height. That means that the trees with a DBH between 0 and 5.9 cm are measured on a sampling area of 25 m^2, the trees with a DBH between 6 and 11.9 cm on a sampling area of 50 m^2, the trees with a DBH between 12 and 29 cm on a sampling area of 150 m^2, the trees above a DBH of 29 cm on a sampling area of 500 m^2. In these plots tree position (only trees larger than 12 cm), DBH, height and other inventory parameters were measured. Altogether we have collected data from 712 plots in the test areas.

In 2003 forest structure mapping will be done. During the summer of 2003 homogenous forest patches (developmental phases) have been mapped by a combination of ground work and interpretation of aerial photos.

The first step to analyse the data was an accuracy assessment of the digital terrain model (DTM) and of the digital crown model. The main questions were: How is the accuracy in dependency on tree species, tree height, slope and what will be the effect of an improved DTM accuracy, by other filter techniques.

METHODS

Height measurements on the ground

The ground work was conducted in the summer season 2002. The measurements were carried out with the "Vertex III" system. This altimeter uses subsonic impulses for the distance measurements. The basic principle for the measurements is the trigonometric principle. For the height measurements we used the definitions of Kramer (1995).

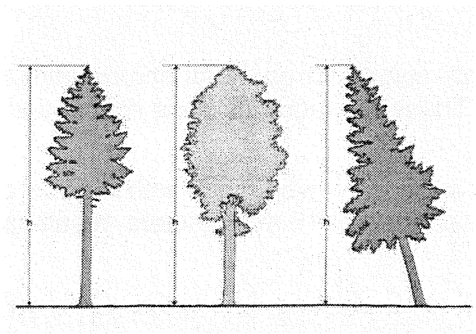

Figure 2: Definitions of tree height for coniferous and deciduous trees as well as for angular trees according to KRAMER.

Creation of the DSM and DTM

The coordinates (Northing, Easting and Elevation) for the desired coordinate system were calculated for each lidar stripe, using data from the GPS processing, the aircraft INS (Inertial Navigation System) and the single laser distance measurements.In a following step, the points were firstly sorted into a grid with a spacing of 0,5 m and a height resolution of 0,01 m. The Data for the DTM then was resampled to a destination spacing of 1m. The calculated DSM data (Digital Surface Model) was processed from the first return lidar data, with an emphasis on the higher values. The calculated DSM data contains height information on buildings, vegetation, terrain and other features. Noisy pixels were removed by filtering. The DTM-data (Digital Terrain Model) was processed from the last echo data with an emphasis on the lower values. In order to obtain a model without buildings and vegetation, a further filtering step was necessary. Both models may show spots of total reflection. The holes resulted from the DTM filtering, as well as spots of total reflection are closed by interpolation. Data procession was done with the TopPit software from TopSys (TOPOSYS, 2002).

Data preparation and analysis

In the first step the binary data was clipped to the sizes of the reference sites and transformed to dBase IV format. For the DTM we used the spring flight data while for the DSM we used that from the summer flight. In the next step the point data was rasterized with Arc View GIS 3.2 and the Spatial Analyst Extension. After that the digital crown model (DCM) was calculated by subtracting the DTM from the DSM.

As a second layer, we imported the ground data. For a better visual interpretation of the DCM the resulting grid was converted to a triangulated network (TIN) and the trees of the ground data were visualized as points according to the species and their height (figure 3).

The height of the trees were measured in the DCM and compared with the measurements on the ground. The measurements were only used when it was possible to identify the same tree in DCM and ground data. For the measurements the data was interpreted in the way that we did not measure directly above the bole position (ie. the tree trunk) but at the highest peak of the same tree in the DCM proximal to the bole position of the ground data. Besides the height of the DCM and of the ground measurement we also recorded the distance between the bole position and the assumed tree top.

For the accuracy assesment of the DTM we used measurements of high accuracy GPS in combination with traverse. For the interpolation of the ground data we used a bilinear interpolation. After that the differences between DTM and surveyed data were compared. (Fischer and Knörzer 2002).

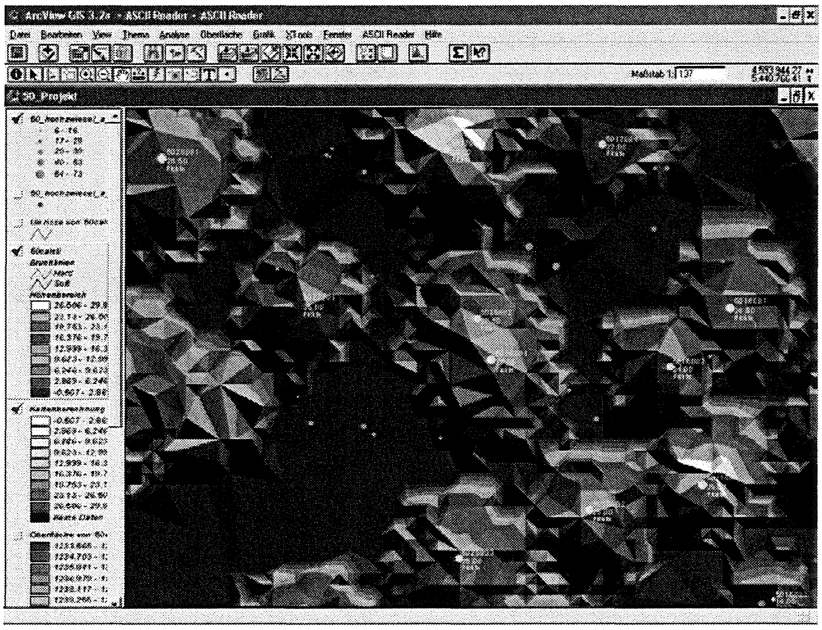

Figure 3: Working environment for the visual interpretation of the tree heights. The dots show the bole position of the trees measured on ground. The TIN represents the DCM.

RESULTS

Accuracy of height measurements

DECIDUOUS TREES

The number of trees measured was 308. The mean of the differences between ground measurements and the DCM was -0,37 m with a standard derivation of 1,43 m. The mean of the absolute differences was 1,01 m with a standard derivation of 0,90 m.

CONIFEROUS TREES

The number of trees measured was 448. The mean of the differences between ground measurements and the DCM was -0,79 m with a standard derivation of 1,25 m. The mean of the absolute differences was 1,14 m with a standard derivation of 0,95 m.

DEAD WOOD

The number of trees measured was 245. The mean of the differences between ground measurements and the DCM was -0,26 m with a standard derivation of 0,79 m. The mean of the absolute differences was 0,55 m with a standard derivation of 0,62 m.

ALL MEASUREMENTS

The number of trees measured was 1001. The mean of the differences between ground measurements and the DCM was -0,53 m with a standard derivation of 1,24 m. The mean of the absolute differences was 1,01 m with a standard derivation of 0,90 m.

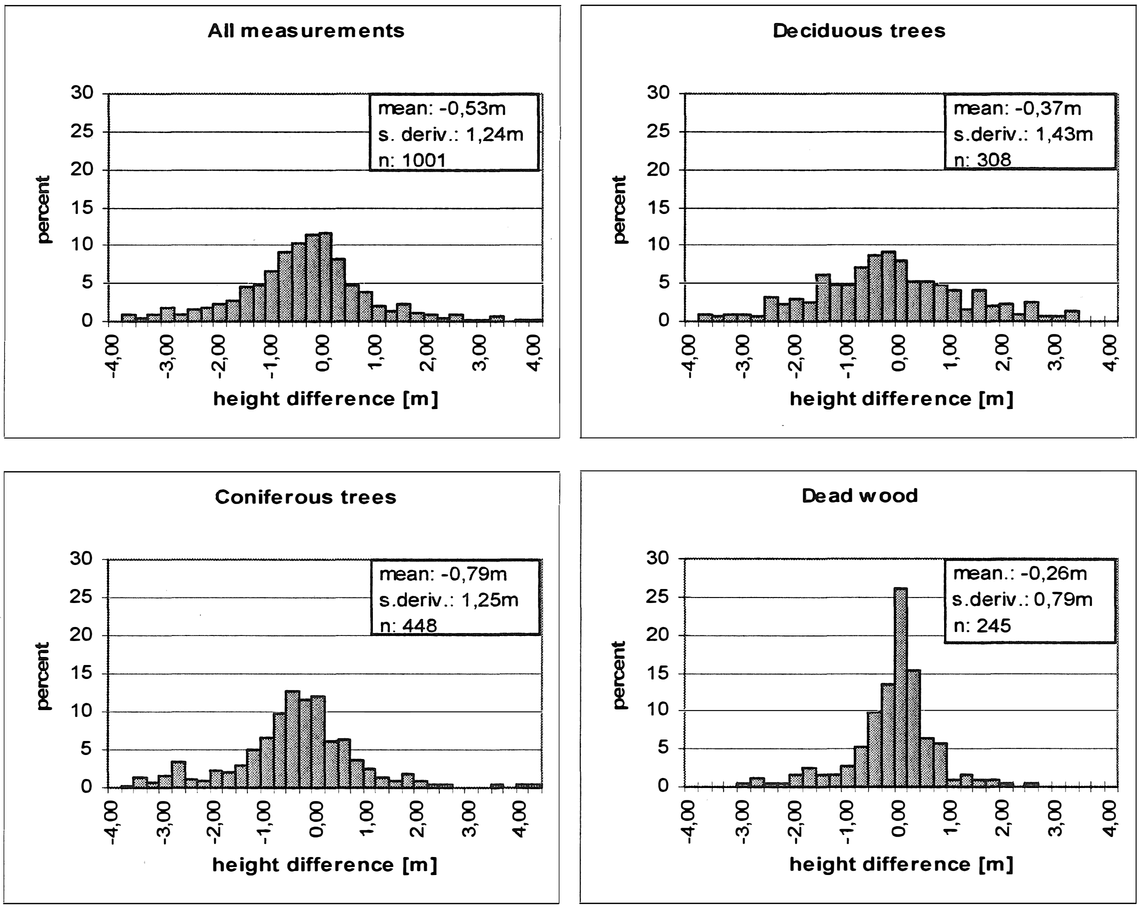

Figure 4: Frequency distributions of the differences between ground measurements and DCM.

Quality of measurements in dependency of tree height

In Figure 5 it is clear that the differences between ground data and lidar data are relatively small in small trees, especially in small coniferous trees. The larger the trees, the larger the scattering of the measured differences becomes. Surprisingly the variation of the differences is not higher in deciduous trees. With increasing in tree height the mean measured difference decrease. The numerical value of the mean measurement difference decreases 4,6 cm per meter in deciduous trees and 3,1 cm per meter in coniferous trees.

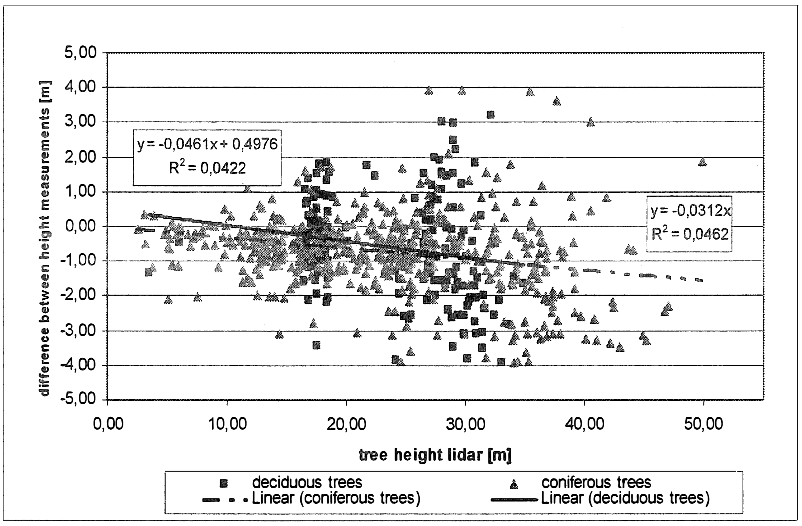

Figure 5: Dependency between the difference of height measurements on ground and out of the DCM and the tree height.

Influence of slope

According to Kramer (1995) the tree height is perpendicular from the tree top to the ground (Figure 1). In Figure 6 the principle of height measurements at slope are shown. Here the tree height is the difference between an assumed vertical line from the root position and the apex of the tree. Because of this principle there is a systematic difference between ground measurements and the DCM for leaned trees calculated the by subtracting the DTM from the DSM. This error is shown in Figure 6. The steeper the angle of the slope and the larger the distance of apex to root position the larger this systematic error becomes.

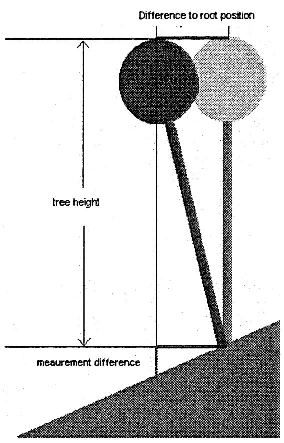

Figure 6: Schematis showing measurement difference between ground measurements and measurements out of the DCM of leaned trees on slopes.

The mean distance between root position surveyed in the field and the tree apex identified in the DCM is only 0,88 m for coniferous trees. For deciduous trees the mean difference is much larger: here the mean is 1,54 m. For all measured threes the mean is 1,08 m. In Figure 7 you can see the measured differences in dependency to the tree heights. The difference between bole position and apex increases with the height of the trees. For the deciduous trees it increases with 2.5 cm per meter and for the coniferous threes it increases at 3.3 cm per meter. The variance is much higher for the deciduous than in the coniferous trees.

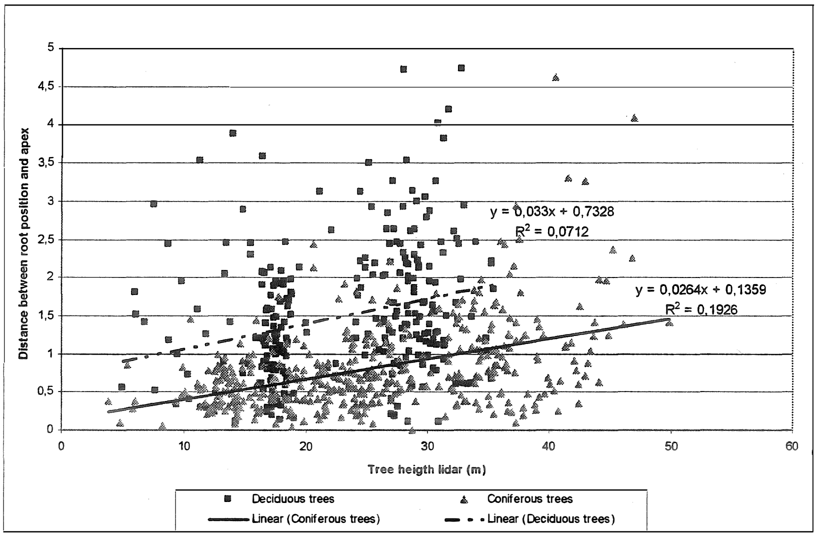

Figure7: Distance between surveyed bole position and lidar tree apex as a function of tree height.

From the mean distance between surveyed bole position and lidar apex and the mean slope of 10,3 degrees of the reference sites, we calculated an average difference of 0,20 m. For 87,4 % of all the measured trees we found an difference smaller than 0,5 m.

Identification of single trees

For this work only the trees measured on the ground, which could be clearly identified as a single tree in the DCM are used for the analysis, as it was done in the high measurements. For the evaluation the trees are classified into three height layers. Top layer: from 2/3 of the top height (medium height of the 100 highest trees) to highest tree; middle layer,1/3 to 2/3 of top height, bottom layer: 5 m to 1/3 of top height. Of the trees in the top layer, 72% could be visually identified. In the other layers the percentage of detected trees is much lower. For more details see Table 4.

Table 4: Visual identification of individual trees out of a DCM with a resolution of 0.5 m.

	Mixed forest	*Coniferous*	*Dead wood*	*Total*
Top layer	69,31%	73,41%	77,68%	72,11%
Middle layer	17,11%	14,57%	59,78%	21,66%
Bottom layer	2,89%	0,74%	40,93%	8,27%
Total	24,38%	36,99%	56,16%	32,77%

Accuracy of the digital terrain model

To evaluate if it would be worth investing more effort in testing and adjust different DTM filter algorithms the differences between the measured tree root position and the DTM were calculated. Together 7654 ground measurements of tree bole positions and ground surface positions were used for the accuracy assesment. These measurements were done at 23 different reference sites. The DTM of the summer flight was only available for 14 reference sites. The mean difference between surveyed terrain height and the DTM was 0,027 m in the data of the spring flight and 0,078 m in data of the summer flight. Standard derivation was 0,286 m in spring and 0,348 m in summer.

CONCLUSIONS

The results of the height measurements with the lidar data shows the underestimation of tree heights especially in coniferous trees. As it was shown in the studies of Naesset (1997) Magnussen and Boudewyn (1998). This is because the used measurement density of the lidar system, used in this study, is still not dense enough to capture the shoots of the trees. These differences are lower in deciduous trees as they have a flatter crown with no single shoots and their shoots are covered with leaves. On the other hand the scattering of the measurements in deciduous trees is larger. It is assumed that this is simply because of the difficulties in measuring deciduous trees from the ground. In dense deciduous stands it is sometimes challenging to decide which is the highest point of the crown as there is no single peak. In addition sometimes the peak is hidden behind a green wall of leaves because the branches of different trees interdigitate; it sometimes even happens that the wrong tree is measured. Further reasons for measurement errors and inaccuracies are detailed discussed in Abetz and Merkel (1962) and Lötsch et al. (1973). The best accuracy we found for dead trees. Here the tree tops are normally broken, so that it is easier to find the spot to measure from the ground. Also the target for the laser beams is larger in comparison to healthy trees. Moreover dead trees are not as tall as healthy trees. This seems to be important because when we differentiated the measurement accuracy between trees larger than 30 m and trees smaller 30 m and found that the accuracy was much better in small trees (mean:-0,32 m; standard derivation: 1,04 m) than in the larger trees (mean:-1,8 m; standard derivation: 1,55 m). It is assumed that this difference is also strongly influenced by the ground measurements. Especially the high trees are pretty difficult to measure from the ground. It is hard to detect the shoots of the trees and the angle for the measurement becomes very steep, when the distance to the root position is not as far as the assumed tree length. But if the ground personal has the right distance it is more difficult to see the top of the tree.

To get information about the accuracy of height measurement from the ground, Bauer (2001) analysed the height measurements and control measurements of 1203 trees. These measurements were done by inventory teams during the regular inventory within the Bavarian state forests. The mean of the measurement differences was 0.07 m, with a standard derivation of 1.40 m. The mean of the absolute differences was 1.01 m with a standard derivation of 0.98 m. It is not surprising that the mean of this data is closer to zero than the one from the lidar data. The interesting thing is that the mean of the absolute differences and variance of this data is almost the same as in this study. Also Eckmüllner and Rieger (2000) found that the error in groundmeasurements was between +/- 1.23 and +/- 1,57 in Norway spruce and +/- 1,64 and +/-1,78 in European beech. Out of this we conclude that the height measurements from the lidar data are, besides the underestimation, at least as accurate as the measurements in standard forest inventories and probably more accurate. We suppose that the variance in our results is strongly influenced by the ground data and probably less by the lidar data. Hyyppä et al. (2000) and Persson et al. (2002) also found that the accuracy of the measurements achieved from the ground is comparable to the height estimations from the lidar data. The problem of underestimation of the height measurements by using the lidar data can be adjusted by the proposed linear regression equations.

To improve the filtering of the DTM has no high priority for our test areas because the measurements are already pretty accurate for forestry purposes. A better algorithm can only enhance the accuracy of tree measurements by some centimetres. Therfore no big effort will be invested in this field within the project.

The principle difference between height measurements according to the definition of Kramer (1995) and out of the DCM has a bigger impact on the results. When the slopes are steeper than 20 degrees must be done a correction. This correction will be done on basis of the measured differences between tree root and apex position collected in this study and the steepness of the slope out of the DTM.

As a result DCMs derived from lidar data are a powerful and fully operational method for tree and stand height determination. The results using this method are at least as accurate as conventional methods basing on the trigonometric principle.

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CLIMATE-INDUCED VEGETATION CHANGE IN CANADIAN BOREAL FOREST AS DETECTED BY AIRBORNE LASER PROFILING

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ABSTRACT

With an objective of detecting possible vegetation change expected to take place due to global warming in terms of quantitative change in forest biomass and leaf area index (LAI), two temporally separated airborne laser profiling missions were flown at a five-year interval along a NS-oriented 600 km transect across the boreal forest of western Canada. The transect extends from Edmonton, Alberta to Cluff Lake, northern Saskatchewan covering the prairie-boreal forest ecotone and boreal forest proper. The first airborne profiling mission was flown in the summer of 1997, and the second in the summer of 2002. The resultant continuous vegetation canopy profiles were calibrated for biomass and leaf area index against ground truth data obtained by a series of plot surveys of biomass and LAI at some 48 sample plots laid out directly under the laser profiling flight pass. A comparison between the two temporally separated estimates of biomass distribution along the entire transect showed characteristic change in five years. The overall change across the transect was negative, which means that the biomass decreased in five years. More specifically, the most drastic decrease occurred in the central 1/3 portion of the transect, with moderate increase in the northern 1/3 and moderate decrease in the southern 1/3. The decrease in the central portion was attributable to a major forest fire of 2002 which consumed considerable amount of biomass. On the other hand, the pattern of change on the both end of the transect is consistent with projected vegetation change expected to results from global warming, i.e. northward shift of the boreal forest zone with its southern side being invaded by prairie and the northern side invading tundra, indicating that the climate-induced vegetation change could well be already in progress.

INTRODUCTION

According to the IPCC (Houghton et al., 1990), the atmospheric carbon dioxide is increasing by 3 ppm annually due to anthropogenic activities, and unless some effective countermeasures are taken immediately, is expected to increase to 560 ppm, double the level of pre-industrial era, by 2030 to result in an increase in equilibrium global mean temperature of 2-5 ℃ and associated change in precipitation. This is a magnitude of change comparable to the shift from the glacial to inter-glacial climate, and should undoubtedly evoke massive vegetation change as projected by Emanuel et al. (1985) and Sweda et al., (1995). In the equilibrium climate of doubled CO2 according to the latter, explicit vegetation change in terms of shift from one category to another in 12 climate/vegetation zones of Koeppen would take place over 1/3 of the global land surface. This prospect of massive global change makes early detection of vegetation change one of the priority topics in vegetation science so as not to be taken aback. However, the research efforts worldwide with ground plot monitoring survey, aerial photography and satellite imagery do not seem to have been rewarded due to lack of coverage and/or insufficient accuracy of measurement. This is where the airborne laser profiling comes in with significantly wider coverage than the ground plot survey, significantly faster digital processing than aerial photogrametry, and much higher accuracy in capturing such quantitative vegetation characteristics as biomass and leaf area index (LAI) than satellite image analysis.

As precursors for detecting the vegetation change possibly under way, we have chosen above-ground biomass and leaf area LAI since quantitative change in these and other measures of vegetation is expected to precede qualitative and explicit changes in species itself or its composition. Another important aspect of these measures of vegetation is that while change in biomass is directly associated with amount of carbon sequestered/emitted by terrestrial ecosystems, one of the important issues requiring precise quantification by the Kyoto Protocol, LAI, defined as the ratio of total leaf area on a given tract of land to the land area itself, is an important indicator of environmental function of forests since climatically influential fixation of carbon dioxide as well as flux of water and latent heat takes place through the leaf as photosynthesis and transpiration.

Considering the GCM projections that global warming would take place unevenly over the globe, i.e. significantly more warning in higher than in lower latitudes, more in the Northern than in the Southern Hemisphere, and more in winter than in summer even in higher latitudes of the Northern Hemisphere (Houghton et al., 2001), we have chosen our study area in the boreal region of western Canada. The choice of boreal forest can also be justified by the fact that it is the most intact expanse of forested region as compared with temperate and tropical forests. Of the boreal region of the world, Canada was chosen for its availability of advanced airborne laser profiling technology at relatively inexpensive cost, and well-developed infrastructure into the boreal wilderness which facilitates ground truth work to calibrate vegetation profile with biomass and LAI measurements on sample plots.

METHODS

Figure 1 show the study area and the airborne laser profiling transect which extends north from Edmonton (53.5°N, 113.5°W), Alberta for 600 km to Cluff Lake (58.0°N, 109.0°W), Saskatchewan. In spite of its length, this transect covers only two vegetation zones, namely the aspen parkland to the south and the boreal forest to the north (Rowe, 1972).

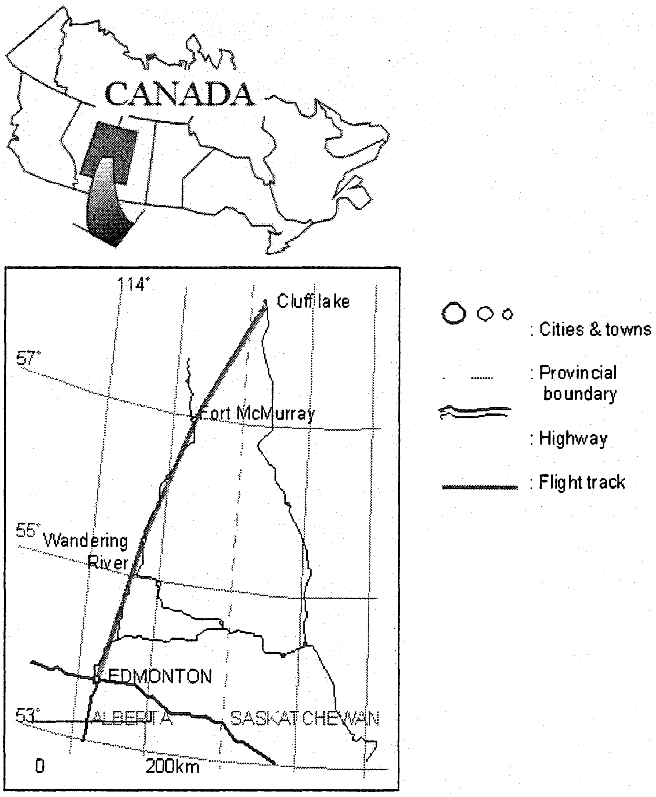

Figure 1: Study area

The aspen parkland is an ecotone between the prairie to the south and the boreal forest to the north, and is characterized by scattered patchy stands of aspen (*Populus tremuloides*) in what originally was grassland of the prairie but has been converted into farmland. The boreal forest is characterized by mosaic of large patches of even-aged, single-species stands of a few limited tree species, i.e. black spruce (*Picea mariana*), white spruce (*Picea glauca*), jack pine (*Pinus banksiana*) and aspen, all regenerated after fires. The airborne laser profiling missions for the present work were flown twice, the first in September 1997 (Sweda et al., 1999; Tsuzuki et al., 1999; Kusakabe et al., 2000: Sasaki et al., 2001) and second in September 2002 with an interval of five years in between. Due to rapid progress in airborne laser altimetry technology, the laser emission frequency in the two missions was different, i.e. 2000 Hz in 1997 and 12,000 Hz in 2002. To make the two missions comparable with each other as well as to squeeze the data, only one measurement for every 5 m of flight distance was sampled, and used in the present analysis. In both cases, reflections from the canopy and ground were distinguished, and then a spline function was fitted to the ground reflection to estimate a continuous topographic profile, which then was subtracted from the canopy profile eventually to obtain vegetation profiles.

To correlate these vegetation profiles with the standing stock of timber, biomass and LAI, a series of ground truth surveys were conducted along the flight track, in which sample plots of size equivalent to square of stand height were set up in representative stands of jack pine, white spruce, black spruce and aspen, as well as in marsh thickets of willow and alder. In each plot, stem diameter at breast height (dbh) was censused with tree height measured on scores of representative sample trees, and more detailed measurement of stem form, branch weight and leaf area and weight on several sample trees felled in each plot. Then with these data, allometric regressions on dbh were established for stem volume, branch and leaf weights and leaf area, with which the standing stock of stem volume, aboveground biomass and LAI were calculated for each of the 48 plots surveyed.

A comparison between the laser profile and ground truth revealed that both the biomass and LAI correlate well with the integration of vegetation profile, i.e. the area under the vegetation profile. As dimensional analysis indicates, biomass can be regressed linearly upon the profile area, while LAI can be upon that to the power of 2/3. So far as the correlation itself is concerned, regression by species showed better results. In the present analysis, however, no such distinction was made, and single regression equation was applied to the aggregate of all the species involved as shown in Figures. 2 and 3 since the species distinction by vegetation profile itself is still under development and not applicable yet.

RESULTS

The 1997 and 2002 flight courses are shown in Figure 1. At a scale shown in the figure the both courses look exactly the same, but they were apart from each other to a maximum of a few hundred meters in the distance perpendicular to the direction of flight as shown in the enlarged insets. However, in view of the total distance covered by the profiling flights, and the large patches of uniform vegetation of limited tree species regenerated after wild fires on uniform topography of alternating flat plateaus and gently rolling hills, this much of difference was considered negligible.

To show the vegetation characteristics of the entire transect, the vegetation profile resulting from the 1997 mission is given in Figure 4, in which an actual spot measurement sampled at every 100 m is shown in a thin vertical spike, while the general trend obtained by smoothing them are shown in thick curves. The figures give us considerable information about the nature of the boreal forest as well as the potential of the airborne laser profiling. First of all, it clearly shows the vegetation boundary between the aspen parkland and the boreal forest proper at some 150 km north of Edmonton as a drastic change in mean vegetation height as well as in the pattern of individual spikes. In the aspen parkland the mean vegetation height is relatively low at 3-4 m due to spotty distribution of aspen stands with considerable proportion of treeless grassland, whereas it gets more than twice as high in the boreal forest section due to continuous cover of forest canopy. The low profile areas around 300 km from Edmonton and toward the northern end of the transect are burns from recent fires. The vegetation profile also indicates that the center of height growth for the boreal forest lies at around 250 km from Edmonton, from where the height decreases both northward due to increasing coldness and southward due to increasing aridity.

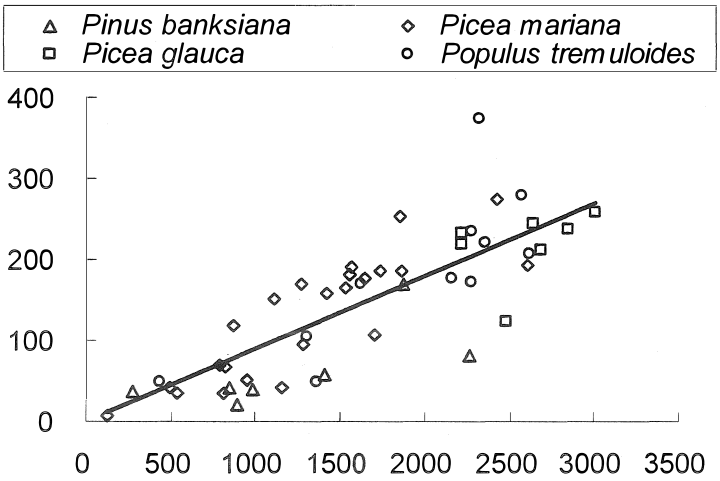

Figure 2: Regression of LAI upon vegetation profile area.

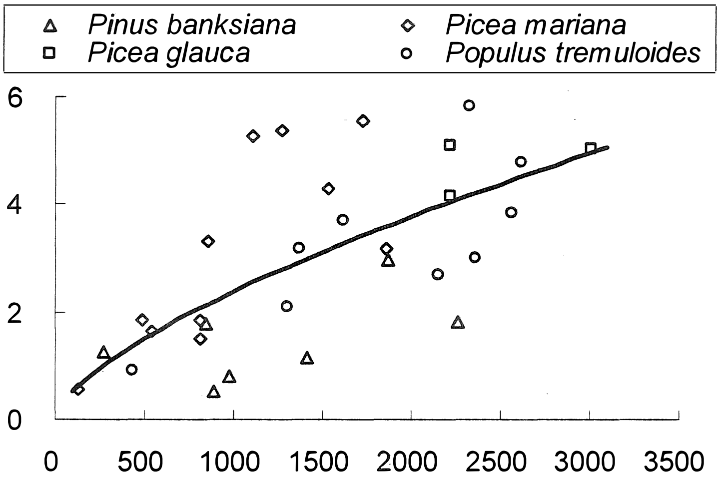

Figure 3: Regression of LAI upon vegetation profile area.

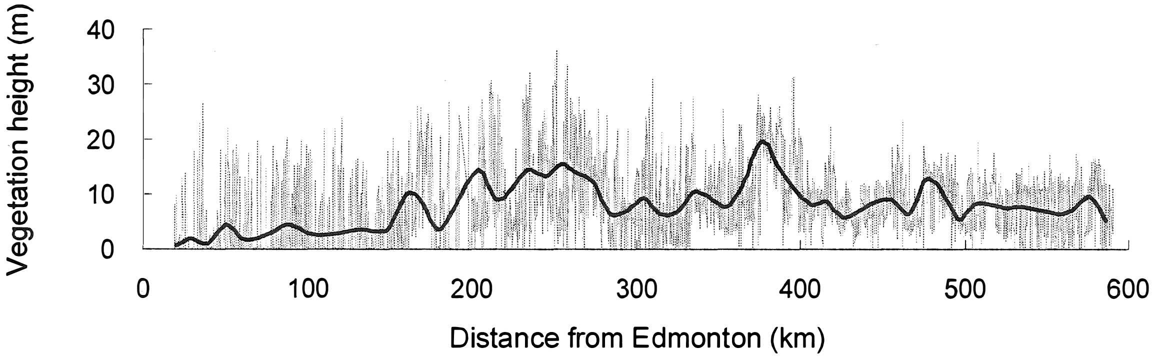

Figure 4: Vegetation profile from Edmonton to Cluff Lake.

Figure 6 shows the changes in aboveground biomass and LAI in five years. In this figure red lines indicate 1997 distribution and green lines do 2002 counterparts, with blue lines showing the difference between them (i.e. 2002-1997). During this five-year interval, the overall mean biomass across the whole transect decreased by 5 DMt/ha (dry matter ton per hectare) from 48 to 43 DMt/ha. A close examination shows that this decrease is mainly attributable to that in the middle 1/3 section of the transect where a major fire (House River Fire) consumed a considerable part of the biomass in the summer of 2002 according to Hogg of the Northern Forestry Centre, Canadian Forest Service (personal communication). As shown in the figure, the decrease in biomass in the central portion of the burn amounted to 38 DMt/ha. On the other hand, though somewhat obscured by similar effect of minor fires, the southern 1/3 and northern 1/3 sections are cancelling the change with slight decrease in the former and similarly slight increase in the latter. As indicated in the figure, decrease in the southern 1/3 amounted to 0.8 DMt/ha, whereas increase in the fire-free portion of the northern 1/3 did 2.2 DMt/ha. LAI also showed a similar pattern of change with significant decrease in the middle section, slight decrease in the southern section and slight increase in the northern section.

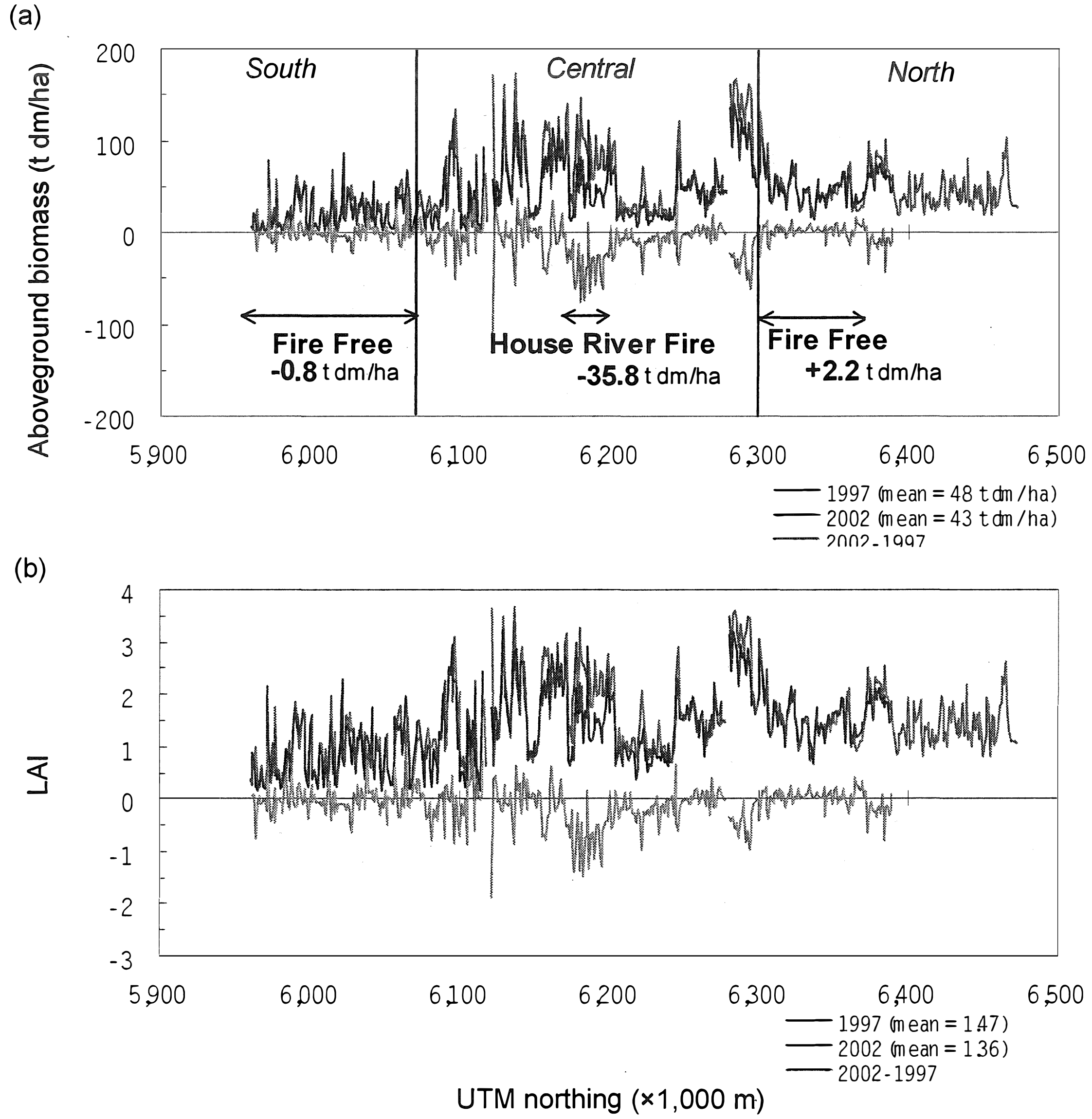

Figure 5: (a) Difference (blue) in aboveground biomass between 1997 (green) and 2002 (red), and (b) difference (blue) in LAI between 1997 (green) and 2002 (red).

Though slight, this change in biomass and LAI corresponds very well with the projected pattern of climate change and associated projection of vegetation change in response to doubling atmospheric CO2, in which the expected warming of the region as a whole helps the boreal forest grow better toward north, but increasing aridity toward south inhibits tree growth to allow the prairie and the ecotone of aspen parkland to invade north. Thus the change in biomass and LAI in the last five years can be reasonably interpreted as a realization of the quantitative phase of the projected vegetation change. According to Hogg (personal communication), forests of central Alberta to which the southern portion of our transect belongs are dieing back partly due to severe draught of 1998 and partly due to outbreak of tent caterpillars. These factors as well as the forest fire can be considered as individual facets of multi-faceted effects of global warming as any disease can be a direct cause of death of individual organisms due to aging.

CONCLUSIONS

The pattern of change in biomass and LAI along the 600 km transect detected by airborne laser altimetry flown in a five-year interval matched well with the pattern of vegetation change expected to take place due to global warming. Although supported by local circumstantial evidences of consumption and decline of forests respectively by fire and drought and insect infestation, this result of decreasing biomass and LAI in the southern to central portion of the boreal forest region is not consistent with more global estimates resulting from analysis of satellite imagery. For example, Myneni et al. (2001) report that forest biomass is increasing in mid and high latitudes of the Northern Hemisphere as a whole. Two possible reasons can be considered for this discrepancy. Either southwestern Canada is a peculiar region where biomass is decreasing against the general trend of temperate and boreal zones of the Northern Hemisphere, or our transect was deviated too south so that biomass decrease due to drying overwhelmed increase due to warming. In other words, our airborne laser profiling would have shown overall increase in biomass as does the satellite estimate if it were flown into tundra covering not only the whole boreal forest region but also the southern end of tundra where forest may be invading.

ACKNOWLEDGEMENTS

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DETECTION OF HARVESTED TREES AND ESTIMATION OF FOREST GROWTH USING LASER SCANNING

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ABSTRACT

The applicability of small footprint, high sampling density airborne laser scanner for estimation of forest growth and detection of harvested trees is demonstrated. Two laser acquisitions - one in September 1998 and another in June 2000 - were carried out using Toposys-1 laser scanner in test site (Kalkkinen), 130 km north of Helsinki. Three-dimensional tree height models were calculated for both data sets using raster-based algorithms. Object-oriented algorithms were developed for detection of harvested trees and forest growth estimation. Out of 82 field-checked harvested trees, 65 trees could be automatically detected. All mature harvested trees were detected; problems were encountered mainly with smaller trees. Forest growth was tested at tree, plot and stand levels. Applied methods included an object-oriented tree-to-tree matching algorithm, interactive orientation using point cloud and statistical analysis. The precision of the estimated growth, based on field checking or statistical analysis, was about 5 cm at stand level and about 15 cm at plot level. The authors expect that the methods may be feasible in large area forest inventories where permanent sample plots are used; the described methods may be applied to replace a large number of permanent plots with laser scanning techniques.

1. INTRODUCTION

Forests are living ecosystems, characterized by continuous natural and anthropogenic processes. Natural processes include annual growth, mortality or natural disasters, whereas cutting or cultivation presents a typical anthropogenic action. Forest changes can be found by either detecting the actual forest and land use class resulting from a change or executing an inventory twice on the same area (Varjo and Mery, 2001). Remote-sensing-based methods utilize the former approach while national forest inventories typically use the latter. For example, the National Forest Inventory of Finland (Tomppo, 1991; Tomppo, 1997) utilizes permanent sample plots to monitor tree recruitment, growth, health and mortality. Tree coordinates on permanent plots are registered to identify them during the next inventory.

Remote sensing techniques have been widely applied during the last decades to replace or support the conventional forest inventories. Manual photointerpretation has been widely used for forest planning in Europe since the 1960's (Avery 1966). The development of more automated techniques for forest inventory has been more difficult, and low success of satellite data application has been due to high information requirements (e.g. tolerated error in standwise inventory is typically 15 % for main stand parameters).

The development of high-resolution aerial photographs has made it possible to use pattern recognition methods to detect individual trees (Gougeon, 1995; Dralle and Rudemo, 1996; Brandtberg and Walter, 1998). Recently, the process towards characterization of individual trees has been realized using a laser scanner (Brandtberg, 1999; Hyyppä and Inkinen, 1999; St-Onge, 2000; Hyyppä *et al.*, 2001a,b; Lim *et al.*, 2001; Persson *et al.*, 2002; Popescu *et al.*, 2002). Hyyppä and Inkinen (1999) demonstrated the possibility to measure single tree parameters (height, crown width, tree species). Based on Persson *et al.* (2002), tree crown can be automatically delineated with up to 70% accuracy and tree height can be measured with an accuracy better than 1 m.

The detection of changes in forested areas using remotely sensed imagery has not been accurate enough so far to meet the assessment requirements, especially regarding slight or moderate changes such as thinning or forest damage (Häme, 1991; Olsson, 1994; Varjo, 1996). Advanced techniques such as segmentation may improve change detection (Pekkarinen, 2002). Traditionally, change detection methods have been pixel-based. It is, however, possible to carry out an object-oriented change detection analysis by using object-oriented image analysis and post-classification comparison. Concerning forest inventory, suitable object is individual tree.

The objectives of this paper are to present and test a single tree based approach for tree height growth estimation and to demonstrate a data processing stream for automatic detection of harvested trees in boreal forest zones using laser scanner data, acquired at autumn 1998 and early summer 2000.

2. METHODS

2.1 Test Site and field data collection

The test site applied for this demonstration is located in Kalkkinen, southern Finland, 130 km north of Helsinki. State forest and some private forests of about 100 hectares in total were selected for the study. The main tree species of the test site, dominated by small hills, are Picea abies (Norway spruce) (49%), Pinus sylvestris L. (Scots pine) (35%), Betula verrucosa and Betula pubescens (silver and downy birches) (11%). During the last decades there have been few silvicultural operations in most of the state forest and some cuttings have been accomplished in the private forest. 20 stands in the test site were selected for general demonstration of growth estimations. The average size of 20 stands is 1.2 hectares.

Field measurements were carried out in August 2002 to collect ground truth data. For the validation of automatic detection of harvested trees, 26 individual harvested trees and 15 clusters consisting of total 56 young harvested trees were found. For the validation of growth estimations, tree height and shoot elongation were measured. With a tacheometer and a glass fibre, the height of the small trees was first measured, and then five consecutive shoots below the top of the tree, giving the height of the tree after annual growth periods between 1997-2002. Taller trees were measured using a tacheometer (Sokkisha SET3C) and a theodolite (Wild T2002 with Distometer Di2002). First, the distance to the tree was measured and the angles to the top of the tree and to the top of shoots were measured. The heights were then calculated. Only pine shoots were measured, since annual shoot growth of other tree species is much more difficult to determine. One of the difficulties in the comparison between the reference data and laser-derived values was the two-year separation between the two laser acquisitions. In boreal conditions the annual growth period lasts approximately from the beginning of May to the end of August. Height growth differs between tree species. According to Kanninen et al. (1982), in Finland most height growth of Scots pine is completed by 15 June.

2.2 Laser Acquisitions and preprocessing

The Toposys-1 laser scanner was selected for this demonstration due to its high sampling rate and steep incidence angle. The laser data were acquired on 2-3 September 1998 and 15 June 2000. The test site was measured from an altitude of 400 m resulting in a nominal sampling density of about 10 measurements per m^2. The survey altitude was selected to provide the number of pulses needed to resolve individual trees. To conduct object-based analysis, trees should be delineated based on a tree height model.

The tree height model was computed as the difference between the digital surface model (DSM) representing the top of the crown and the digital elevation model (DEM). The DSM of the crown was obtained by taking the highest elevation value (z value) of all laser hits within each pixel (50 cm). The value for missing pixels was obtained using Delaunay triangulation and linear interpolation. To generate a DEM from laser scanner data, points that reflected from trees and buildings were classified as non-ground hits. After classification, the DEM was calculated using ground points. The accuracy of the DEM algorithm was tested by Ahokas *et al.* (2002) and an accuracy of 14 cm in a hilly, forested environment was obtained.

Segmentations were performed on derived tree height models of both acquisitions (1998 and 2000) and on 20 selected stands for delineation of single trees using commercial software (Arboreal Forest Inventory Tools of Arbonaut Ltd.). The algorithm was described in Hyyppä *et al.* (2001a), and the performance of the segmentation algorithm compared to two other algorithms (developed at Joanneum Research in Austria and University of Freiburg in Germany) is described in Hyyppä *et al.* (2001b).

2.3 Automatic Detection of Harvested Trees

The method for detection of harvested trees was developed on the basis of a difference image; each pixel value in the image corresponding to the tree height model of the year 2000 was subtracted from its corresponding pixel value in the image of the tree height model of year 1998. The resulting difference image represents the pixel-wise changes between the two dates. Harvested trees can be clearly recognized and located visually. In this study, an automatic method to locate the trees based on segmentation of the difference image was developed. A threshold value was first defined in order to distinguish major changes. Then, a specified filter reducing noise-type fluctuation was applied. Finally, the location and number of harvested trees was determined by analyzing the obtained segments. Figure 1 showed one example of the analysis of harvested trees.

2.4 Estimation of Tree Height Growth

Based on earlier work (e.g. Hyyppä and Inkinen, 1999), the height of individual trees can be obtained with an accuracy better than 1 m. However, when the trees are typically growing at a rate of 5 cm-1 m per year in the boreal forest zone, it is extremely difficult to estimate single tree growth. Especially, the tip of the trees can be missed by the laser hits. Practical forest operations require average growth estimation at plot or stand level, not at tree level. That can be obtained by calculating the difference of the means of all tree heights taken at two acquisitions. However, activities, such as selective thinning or cutting, occurred after first acquisition could lead to false interpretation and to systematic errors in interpretation, if they are not considered in the analysis. Therefore an object-oriented tree-to-tree matching algorithm was developed to locate the same trees existed on both acquisitions. Single tree heights from laser data was obtained by taking the highest value of each corresponding tree segment. Location of the trees was defined as the location corresponding to the highest value of the segments. If locations of two segments, each from one acquisition, were within a specified distance threshold, then these two segments were considered as a match. The growth of height of single trees was estimated by the tree height differences of matched trees (laser-derived growth). Growth on a stand level was determined by mean difference for all matched trees (laser-derived mean growth). The standard error (standard deviation divided by the square root of number of matched trees) was used to evaluate the precision of the tree height estimates at stand level. DEM compensation was applied optionally (same DEM was applied for both acquisitions after removal of the systematic error).

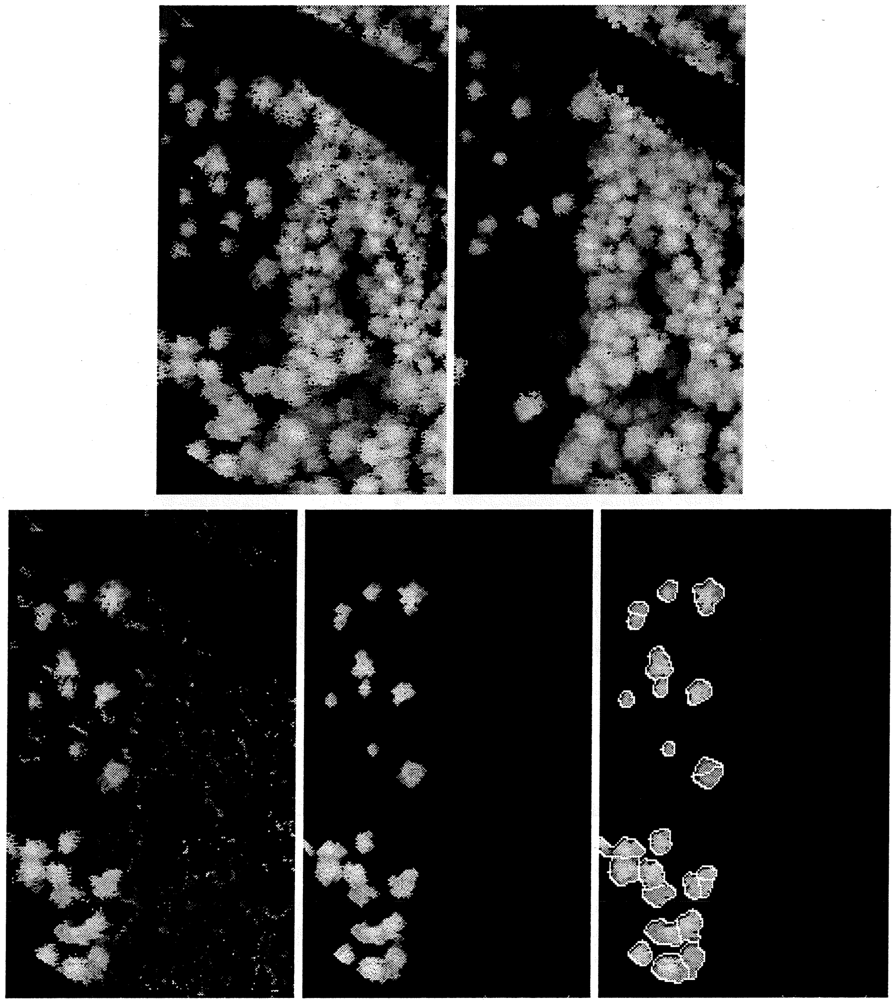

Figure 1. Data processing stream for automatic detection of harvested trees. Upper left: data of 1998, upper right: data of 2000, lower left: difference image, lower middle: thresholded and filtered image, and lower right: segmentation image.

In addition to the automatic technique developed above, an interactive method utilizing point cloud data was tested to verify the single tree and plot level accuracy. First, individual trees were found using segmentation and a tree-to-tree matching was applied to the selected test trees. The point cloud of these trees was extracted from the laser data. The interactive orientation method depicted in Rönnholm et al. (2003) was utilized to match the point clouds of selected trees between laser acquisitions. The height difference of data sets was interpreted using the lowest branches of the trees from the both viewing directions (NS and EW). Shifts were calculated for each group of trees independently. In this paper, the difference between the maximum tree hits was considered as growth (Figure 2).

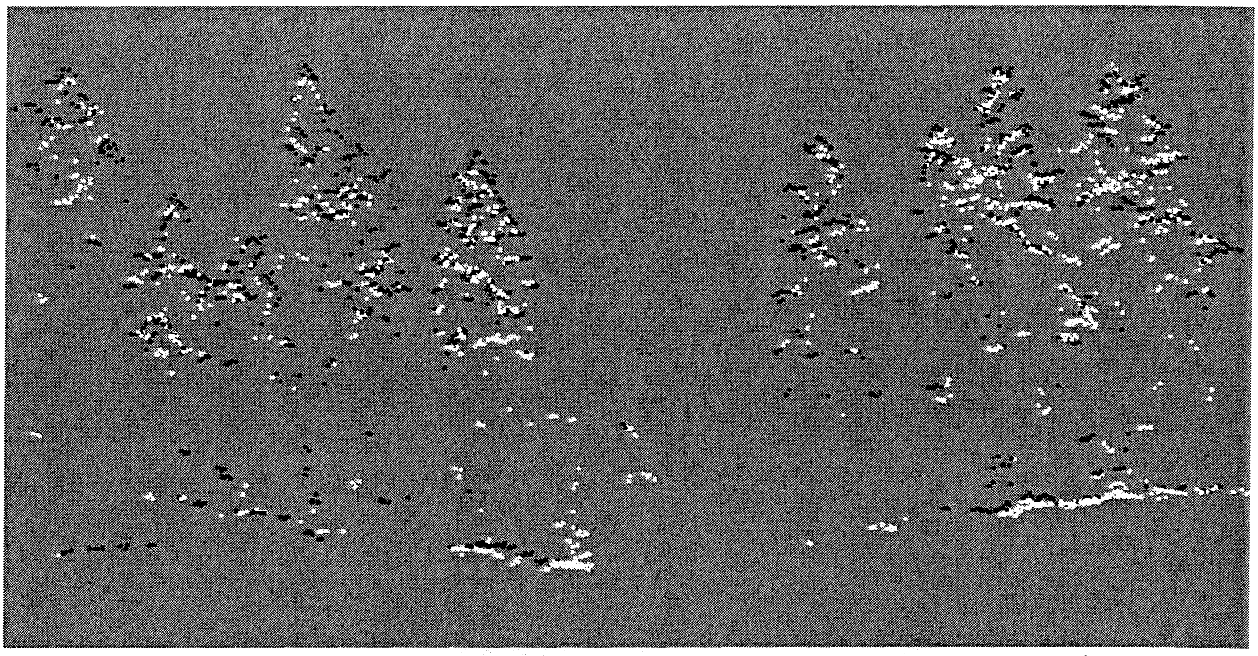

Figure 2. Point clouds for selected trees (black corresponding to acquisition in 2000 and white corresponding to acquisition in 1998). The data sets have been interactively matched using the lowest branches.

3. RESULTS

3.1 Analysis of Automatic Harvested Trees Detection

Results obtained by comparing of automatically derived harvested trees using methods described previously with field measurements showed that two small harvested groups (radius of crown areas less than 1 m) were missed. The rest of the harvested trees or groups of cut trees were detectable, although the number of recognized harvested trees were different (Table 1). The recognition of small deciduous trees was the most problematic. It was quite encouraging to notice that several partially harvested trees (big branches cut off) near a new power line were automatically recognized even though they were neither circular in shape nor big in size. Figure 1 showed one example of the analysis of harvested trees.

Table 1. Verification of harvested tree detection

	Number of single harvested trees	Number of trees and number of corresponding groups
Field-measured	26	56/15
Laser-derived	31	34/13

3.2 Analysis of standwise growth

Laser-derived growth at stand level was calculated for 20 stands using the depicted automatic algorithm for forest growth. The results are shown in Table 2. In addition to height growth, standard deviation (S.D.) and standard error (S. E.) of the mean were obtained as well. The standard error of the mean implies the precision of the growth estimate. Typically, the standard errors were less than 5 cm and in all cases less than 10 cm.

Table 2. Statistics of standwise height growth.

Stand	Number of matched trees	Height (m) 2000	Mean Growth (m)	S.D (m).	S.E. (m)
126	44	8.90	0.66	0.22	0.03
128	923	25.45	0.10	0.38	0.01
135	87	17.14	0.48	0.40	0.04
136	780	7.09	0.60	0.56	0.02
137	444	21.38	0.22	0.32	0.01
139	52	16.87	0.41	0.56	0.08
140	206	21.42	0.20	0.49	0.03
147	333	22.64	0.04	0.35	0.02
148	64	21.46	0.04	0.35	0.04
149	45	19.26	-0.01	0.28	0.04
153	245	24.67	0.09	0.26	0.02
156	146	22.08	0.05	0.30	0.02
158	245	19.45	0.16	0.40	0.03
185	110	23.21	0.09	0.38	0.04
188	60	16.14	0.11	0.50	0.06
189	48	21.77	0.20	0.42	0.06
190	132	8.58	0.58	0.59	0.05
191	92	6.26	0.75	0.38	0.04
192	92	18.55	0.21	0.29	0.03
200	49	15.23	0.67	0.38	0.05

After tree-to-tree matching, it was possible to have a scatterplot between the heights in 1998 and 2000 (Figure 3). The mean of the differences gave the mean growth, whereas the standard error depicted the precision of the results. Due to the inaccuracy of the obtained individual tree growth, the precision of the estimation was based on obtaining a large number of growth estimates. This also allowed the estimation of the growth as a function of tree height within the stand and with confidence limits, as demonstrated in Figure 4, which is also a necessity in order to understand the variability of growth within one stand.

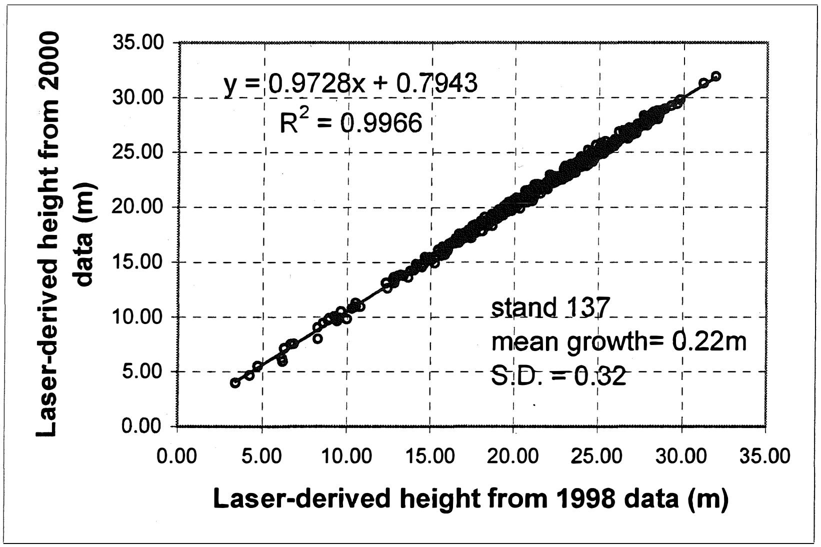

Figure 3. Scatter plot showing relation between matched tree heights between years 1998 and of 2000. The systematic difference gives the mean growth and standard deviation describes the uncertainty to measure single tree heights.

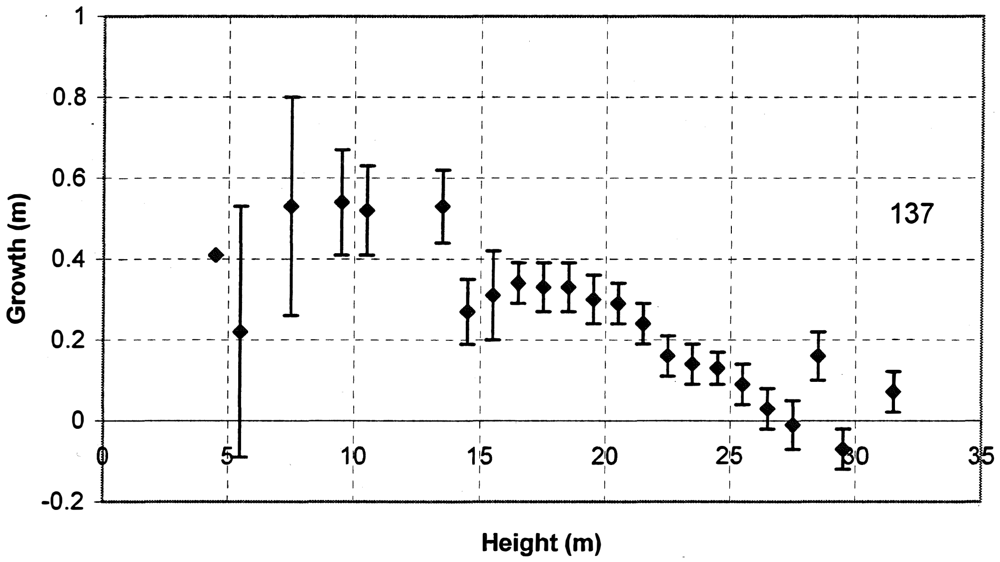

Figure 4. Tree height growth with confidence intervals as a function of height for one stand. Tree heights were divided with about 1 m intervals. Height and growth are the average values of all trees within the intervals.

Table 3 summarizes the results obtained using the point cloud and interactive orientation for selected trees. In the Table 3, also values using previously described automatic method were given with and without DEM compensation.

Table 3. Comparison of treewise growths.

Stand	Tree	Growth using interactive orientation and point cloud	Growth using automatic method without DEM compensation	Growth using automatic method with DEM compensation	Reference growth
137	1	0.82	0.72	0.80	0.43
137	3	0.65	0.70	0.74	0.60
137	4	0.02	0.00	0.14	0.69
137	16	0.32	0.50	0.47	0.41
137	19	0.78	0.89	0.82	0.43
137	20	0.12	0.19	0.15	0.23
137	22	0.71	0.76	1.19	0.56
137	23	0.36	0.55	0.57	0.25
	Average	0.47	0.54	0.61	0.45
139	8	0.62	0.04	0.75	0.63
139	9	0.62	-0.11	0.75	0.55
139	10	0.45	-0.45	-0.39	0.68
139	12	0.26	-0.08	0.39	0.36
139	17	0.88	0.67	1.01	0.54
139	18	0.23	-0.27	-0.04	0.47
139	19	-0.39	-0.56	-0.26	0.33
	Average	0.38	-0.11	0.32	0.51

In stand 137, the field-measured average growth was 45 cm. Using interactive orientation method, 2 cm deviation from the reference mean was obtained and 9 cm deviation with the automatic method. Out of eight trees, the growth of 5 trees could be estimated within 15 cm with the interactive orientation method and within 20 cm using the automatic method. The standard deviation of these two DEMs was 17.7 cm. The use of the DEM compensation modified the growth estimate by 7 cm.

In stand 139, the field-measured average growth was 51 cm. Using interactive orientation method, 13 cm deviation from the reference mean was observed. Without tree 9, the deviation of the mean would have been 3 cm. However, using the automatic growth model, deviation of 62 cm without the DEM compensation and 19 cm with the DEM compensation was observed. What was the cause for such a difference in the results? By comparing the laser-derived elevation models from the two years, it was found that in the stand 139, there was a systematic shift of 37 cm to the level shown in stand 137 and the standard deviation of these two DEMs was 35.2 cm. Obviously, the problems in the creation of the DEM affected the growth analysis. The matching of the data sets by using the lowest branches in interactive orientation method lead, therefore, to improved results.

Is it possible to measure single tree growths? It is obvious, that by taking just the maximum value of each tree, the probability of not getting the tip of tree measured is quite high. However, based on the Figure 2, one could draw a conclusion that single tree growth can be estimated on favourable conditions. That requires either the comparison of larger number of corresponding laser points of two different laser acquisitions or the comparison of model created using different acquisitions.

4. CONCLUSIONS

Automatic detection of harvested trees was demonstrated. Methods were developed in order to detect such trees from a difference of tree height models. Out of 82 field-checked harvested trees, 65 trees were automatically detected. All mature harvested trees were detected. The data did not allow the monitoring of some of small trees in a reliable manner.

Forest growth measurements using multi-temporal laser scanner data were also demonstrated. Methods were developed and depicted to derive forest growth at various levels. The major requirement for the growth analysis was object-oriented matching between the tree height models. By applying interactive orientation, it was shown that plotwise mean growth can be estimated with accuracy better than 15 cm. Typical standard error for mean growth estimation at stand level was less than 5 cm. About 50 % of the individual tree growths were measured within 15 cm by using only one laser point to represent the tree height. The major problems in getting accurate tree growth estimates are errors in DEM, segmentation, and tree-to-tree matching.

One critical aspect that could strongly affect the results is the segmentation of single tree. The algorithm applied tends to merge two or more trees in one segment rather than split one tree into two separate segments. Presently, most of the algorithms used for segmentation of laser scanning data are developed for aerial images, thus does not take full advantage of 3D information of laser scanner data.

Tree to tree matching is directly influenced by single tree delineation as well as matching algorithm. In this study, matching rate for 20 stands varied significantly. The lower of matching rate, the smaller number of tree could be monitored automatically. Therefore improvement in tree to tree matching is important for obtaining an unbiased estimation of tree growth at plot and stand levels.

5. ACKNOWLEDGEMENTS

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PREDICTION OF FOREST VARIABLES USING LIDAR MEASUREMENTS WITH DIFFERENT FOOTPRINT SIZES AND MEASUREMENT DENSITIES

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ABSTRACT

The possibility to estimate tree height and stand volume from airborne laser measurements and the effect of using different laser measurement densities on estimation errors have been evaluated in two independent studies in southern Sweden.

The first study was made using 28 circular plots within a costal Scots pine stand (*Pinus sylvestris* L). A helicopter borne laser scanner having emissions at 532 and 1064 nm, but only the green beam was used to estimate tree heights and stem volume. The laser data were acquired during three independent missions made in June, October, and December 1991. Four different laser footprint diameters between 0.75 and 3.0 m were used. The sampling distance in each dataset was equal to the footprint diameter. It was found that the optimal footprint size for tree height prediction changed between different acquisition dates. The result shows that the most reliable height estimates were obtained using less than 4.5 m between individual laser shots. A laser derived variable including both the waveform area and the laser measured tree height was found to be the most effective variable for predicting stem volume using regression techniques. This model produced a R^2 of 0.78.

A second study was made using a scanning laser that had emission at 1064 nm and a footprint diameter of 3.7 m. The regression models were evaluated using 29 small (0.64 ha) forest stands that had been surveyed using 16 circular field plot (10m radius) in each stand. The results show that the estimation error (RMSE) for tree height and stem volume was 3% and 11% of the average value, respectively. It was found that the predictions of tree height and stem volume were not much affected when reducing the laser measuring density down to 0.10 laser measurements per m^2.

Both studies show that the tested methods gave reliable estimates of tree height and stem volume. An important finding was that the sampling density could be reduced to a certain degree without any significant decrease in prediction accuracy for stem volume and tree height. The possibility to reduce the sampling density will make the laser data acquisition more cost effective.

INTRODUCTION

The potential use of airborne LIDAR systems in forest surveys has now been investigated for more than 20 years. It has been shown that forest variables such as tree height and stand volume can be estimated using data from both profiling and scanning airborne LIDAR systems (e.g., Aldred and Bonnor, 1985; Maclean and Krabill, 1986; Næsset, 2002).

If accurate estimates of forest variables can be produced using LIDAR data, accurate forest management decisions can be made. However, the increase in utility due to better decision making using accurate estimates of variables such as stem volume should be compared with the costs of acquiring the data. One way to reduce the cost when acquiring LIDAR data is to increase flight height, which will result in lower laser measurement density. The effect of different measurement densities on the estimation accuracy for forest variables should therefore be investigated.

The effect of using different footprint sizes for estimation of mean tree height has been investigated in different types of forests. Aldred and Bonnor (1985) found that the tree height was systematically underestimated within softwood forest probably as a result of the tendency for pulse reflections to be somewhat below the conical treetops. Underestimation was also found in hardwood forest. In the hardwood forest, the error was found to be strongly related to beam width, with lower errors using wider beams. This difference due to beam size was less evident in softwood forest. The results indicated that a wider beam was optimal for height estimations in deciduous forest compared with the beam size optimal for softwood forest.

For the first profiling LIDAR systems, the full waveform was usually digitized. These systems were followed by systems developed for terrain mapping without the possibility to save the full return. The use of full waveform digitizing large footprint laser systems could give new possibilities for estimating forest variables. Systems saving the full return have recently been developed as simulators for planned satellite laser sensors but have already proven to be useful for estimation of forest variables in several types of forest including boreal, temperate and tropical forest (e.g., Lefsky et al., 1999a, b; Means et al., 1999; Drake et al., 2002; Lefsky et al., 2002). Lasers with wide beams can also be used to measure ground elevation in dense tropical forest where smaller laser beams would rarely reach the ground. Ground elevation has been measured in tropical forest with a precision of 1 m (Hofton et al., 2002).

The possibility to estimate tree height and stand volume from airborne laser measurements and the effect of using different laser measurement densities on estimation errors have been evaluated in two independent studies in southern Sweden (Nilsson, 1996; Holmgren, 2003). The first study (I) was carried out in a costal Scots pine pine (Pinus sylvestris L.) stand and the second study (II) in hemi-boreal forest in southwestern Sweden. The objectives of study I were (1) to investigate how the use of different laser footprint sizes and sampling densities affects tree height estimates and (2) to determine if stand volume could be estimated using a scanning laser system. The objectives of study (II), were (1) to develop methods for estimation of forest variables at plot level using a medium-sized laser footprint diameter, (2) to validate estimation of forest variables at stand level, and (3) to investigate the effect of different laser measurement densities on the estimation errors.

MATERIAL AND METHODS

Study I

A helicopter-borne LIDAR system was used to determine tree heights and stand volume in an even-aged Scots pine (*Pinus sylvestris* L.) stand located on an island (Ålö; lat. 58°54'N, long. 18°13'E) 50 km south of Stockholm (A in Figure 1; Nilsson, 1996). The test site was 4 ha.

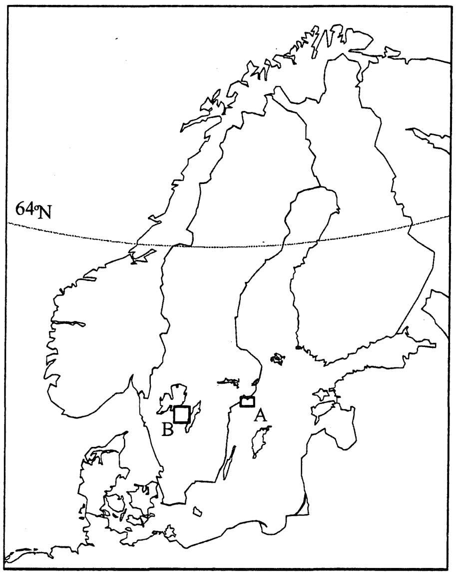

Figure 1. The study areas used in study I (A) and study II (B).

FIELD DATA

Field data were acquired from 28 circular plots (10 m radius). The diameter at breast height was measured on all trees. Tree heights were only measured on a sample of trees. For trees where only the diameter was known, the tree height was estimated using height functions derived using the sampled trees. The stem volume for each tree was calculated based on tree height and diameter (Näslund, 1947). For all plots, mean tree height and stand volume was calculated.

LIDAR DATA

The LIDAR system was helicopter-borne and had emissions at 532 and 1064 nm. Only the green laser was used in this study. LIDAR data was collected at three different occasions by the Swedish Defense Research Agency in Linköping. The first measurements were made in June 1991. In October, the test site was measured for a second time, and the final measurements were made in December 1991. At all three occasions, the LIDAR data was acquired from a flight height of 300 m. The LIDAR system recorded data at a rate of 62 or 160 laser pulses per second. Four different beam divergences in the rage of 2.5 mrad – 10.0 mrad were tested (corresponding to 0.75 m – 3.0 m in footprint diameter). During the flights, the distance between adjacent laser shots in both the along track and the across track direction was set to approximately the laser footprint diameter.

ANALYSIS

Tree heights were derived using an algorithm originally developed for depth sounding. This algorithm could only detect the first four peaks in the return sequence, meaning that the ground surface will not be detected if there are more than four peaks in the laser return.

A variable related to stand volume was derived and used as the predictor variable in a stand volume regression function. This predictor variable was calculated using the laser waveform area and the laser measured tree height (Figure 2).

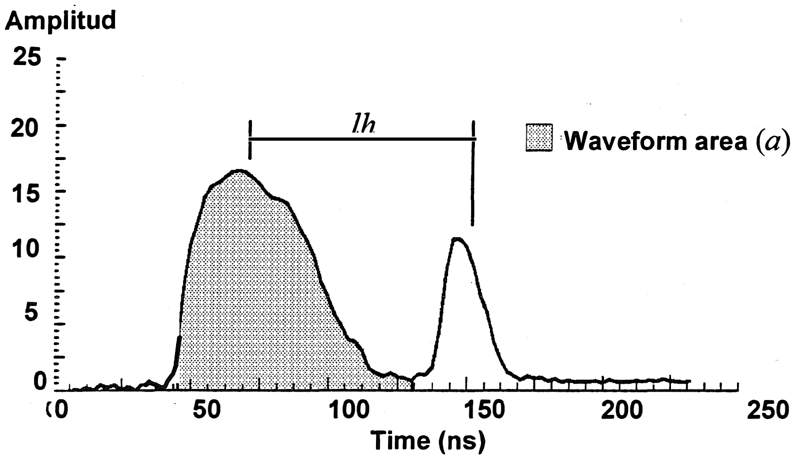

Figure 2. An example of a laser return (waveform). The figure also illustrates how tree height (lh) and waveform area (a) were defined.

Study II

The test site in study II was located in hemi-boreal forest at the Remningstorp estate (lat. 58°30'N, long. 13°40'E) in southwestern Sweden (B in Figure 1; Holmgren, 2003). The dominating tree species were Norway spruce (Picea abies L. Karst.), Scots pine (Pinus sylvestris L.) and birch (Betula spp.). The area was essentially flat with height variation in altitude ranging from 120 to 145 m above sea level.

FIELD DATA

Circular field plots with 10 m radius were used in the study. All trees on the plots with a diameter greater than 5 cm was callipered and their tree species recorded. The age of the dominating trees and site index was also recorded. Height was measured for a sample of trees. The tree height measurements were used to calibrate functions for estimation of height and form height. The static functions used to derive height and form height had stem diameter as the most influential variable (Söderberg, 1992). Volume for all trees was estimated by multiplication of basal area and form height. For these functions, Söderberg (1992) reports that estimates produced by the single-tree functions have a standard deviation of 11% for Scots pine, 13% for Norway spruce, and 15% for birch. The magnitude of these deviations decreases significantly at more aggregated levels (Lindgren, 1984). All inventories of circular field plots were performed using the Forest Management Planning Package (FMPP) (Jonsson et al., 1993).

The field dataset consisted of 10 m radius field plots within 80×80 m^2 squares that had been placed in the middle of forest stands. The requirements for placing a square within a forest stand were: (1) the stand must be within the area of laser measurements, (2) ≥ 70% of the stem volume within the forest stand must consist of coniferous forest, (3) the size and the shape of the stand must allow the 80×80 m^2 square to fit within the forest stand. The inventory of the field plots within the 29 squares was performed in the Spring of 2002. Within each square, 16 field plots (10 m radius) were placed using measuring tape on nodes of a regular grid with 20 m inter-node distance. Only the positions of the centre for the corner field plots were measured with the Differential Global Positioning System (DGPS).

LASER DATA

Laser data were acquired on September 13, 2000. Laser measurements were made from five parallel flight lines in the north-south direction with a length of 2000 to 2500 m and a distance between the flight lines of 200 m. The flight speed was 16 m/s, the scan frequency 16.67 Hz, and the scan width ± 20 degrees. The flight altitude was 230 m and beam divergence 8 mrad which produced measurements with a footprint diameter of 3.68 m. The distance between the laser hits within a scan line was approximately 0.8 m and the distance between scan lines was approximately 0.5 m. Additional measurements were also made from five separate flight lines that were parallel to the main flight lines but shifted 50 m towards the east.

ANALYSIS

The height distribution of laser canopy returns were used for estimation of basal-area-weighted mean tree height and stem volume on the plots. The estimations on plots were aggregated to stand level (80×80 m^2 squares).

The laser reflection points were classified as ground or non-ground using the Terrascan software (Soininen, 1999). Each laser reflection point was also classified into one of the three classes, (1) single return, (2) first return of a double return, (3) second return of a double return. The ground reflection points were used for creating a Digital Terrain model (DTM). The height was derived for each reflection point as the vertical distance to the DTM below.

Several laser variables were derived: mean value, standard deviation, 20th percentile (h_{20}), 40th percentile (h_{40}), 60th percentile (h_{60}), 80th percentile (h_{80}), 90th percentile (h_{90}), and 95th percentile (h_{95}). The vegetation-ratio (D_v) was the number of laser returns with a height > 3 m that was not a second return divided by all laser shots on the plot. The number of three different types of returns with a height value > 3m was derived: (1) number of single returns (n_1), (2) number of first returns of a double return (n_2), and (3) number of first returns of a double return that had their second return with a height value > 3m (n_3). The pulse-type ratio (D_p) was derived as

$$D_p = \frac{n_1 + n_3}{n_1 + n_2} \qquad (1)$$

The relative standard deviation (*relstd*) was derived as the standard deviation of laser returns located > 3m above ground divided by the 95th laser height percentile.

It was assumed that laser canopy height percentiles were related to mean tree height and the vegetation-ratio (D_v) was related to canopy closure. All estimated mean tree heights in this study were basal-area-weighted. Given that tree stem basal area is related to crown volume, a multiplicative model with the vegetation-ratio (D_v) and one laser canopy height percentile would be suitable for estimation of both basal area and stem volume. However, in order to apply linear regression an additive model must be implemented. Basal area, stem volume, laser canopy height percentiles, and the vegetation-ratio (D_v) were therefore transformed with the natural logarithm and these variables were used as variables in the model. It was assumed that the model could yield predictions with higher accuracies if variables related to forest structure were also included in the model. The relative standard deviation (*relstd*) could be a measure of how many laser reflections are located along the side of the tree crown with a higher value for trees with a relative long crown. The pulse-type ratio (D_p) could be related to proportion of crown area that is close to edges because multiple pulses are most likely found at places with fast changes in elevation. All combinations of the extracted laser variables were tested using Dataset A in order to select the most suitable laser canopy height percentile for each model. The residuals were plotted against predicted values and no systematic error could be observed. This resulted in Equation 2 and 3 for prediction of mean tree height (*h*), and stem volume (*v*), respectively.

$$h = \beta_0 + \beta_1 h_{95} + \varepsilon \qquad (2)$$

$$\ln(v) = \beta_0 + \beta_1 \ln(h_{90}) + \beta_2 \ln(D_v) + \beta_3 D_p + \beta_4 relstd + \varepsilon \qquad (3)$$

Stem volume was transformed to original scale by using the exponential function. Correction was then done for logarithmic bias by multiplying the predicted variables by the ratio between field-measured values and predicted values (Holm, 1977).

RESULTS

Study I

Tree heights measured with an airborne laser were found to underestimate the field measured tree heights by 2.1 to 3.7 m. As shown in Table 5, no optimal footprint size could be found.

Table 1. Field measured tree heights, laser measured tree heights, and corresponding standard deviations for the plots covered by different laser data sets

		Laser footprint diameter (m)											
		0.75			1.50			2.25			3.00		
		Field data	Laser data	No. plots	Field data	Laser data	No. plots	Field data	Laser data	No. plots	Field data	Laser data	No. plots
Mean	Jun.	12.6	8.9	21	12.5	9.3	25	-	-	-	12.7	9.5	26
height	Oct.	12.6	10.2	27	12.5	10.0	25	12.7	10.0	26	-	-	-
(m)	Dec.	12.6	9.5	26	-	-	-	12.5	10.4	25	12.7	9.9	28
Stand.	Jun.	1.5	2.1	21	1.4	2.4	25	-	-	-	1.3	2.3	26
dev.	Oct.	1.3	1.7	27	1.0	2.2	25	1.2	2.1	26	-	-	-
(m)	Dec.	1.2	1.7	26	-	-	-	1.1	1.4	25	1.5	1.8	28

The effect of different sampling densities or the distance between individual laser shots on tree height estimates was investigated using the dataset from June with a footprint diameter of 0.75 m. It was found that the most reliable estimates were obtained using less than 4.5 m between individual laser shots.

It was found that the plot-wise mean of the product of the waveform area (*a*) and the laser measured tree height (*lh*) had a strong linear relationship with stand volume (*vol*) (Figure 3). The following regression equation was derived:

$$vol = 17.5 + 0.00372 \cdot \Sigma(a \cdot lh)/n, \qquad (6)$$

where,

vol	=	stand volume (m^3/ha),
a	=	waveform area for a single laser return,
lh	=	laser height for a single laser return (m), and
n	=	the total number of laser returns from each plot.

This equation resulted in an R^2 of 0.78.

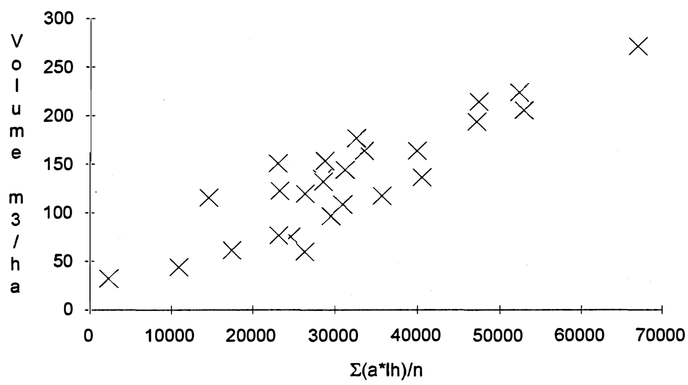

*Figure 3. An example of the relationship between wood volume and the mean product of the waveform area and the laser measured tree height (Σ(a*lh)/n).*

Study II

Regression models were built using the field plots within all validation squares (80×80 m^2) except the one where forest variables were to be predicted. This was repeated until predictions were made for all validation squares. In order to investigate the effect of laser measurement density, the number of laser measurements was reduced before prediction.

For prediction of mean tree height at plots level, the RMSE was 1.07 m corresponding to 6% of the average value. When aggregating the predictions to 80×80 m^2 squares the RMSE was 0.59 m, corresponding to 3% of the average value (Figure 4).

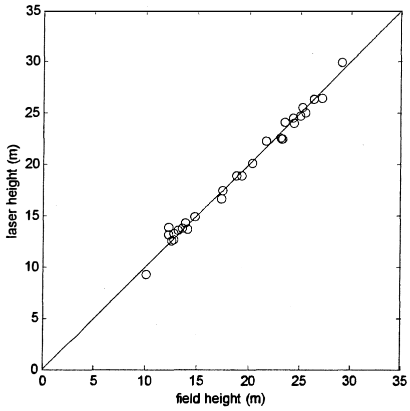

Figure 4. Estimated mean tree height plotted against field measured mean tree height for 29 squares each with the size 0.64 ha.

For prediction of stem volume at plot level, the RMSE was 55 m^3/ha, corresponding to 20% of the average value. When aggregating the predictions to 80×80 m^2 squares, the RMSE was 31 m^3/ha, corresponding to 11% of the average value (Figure 5).

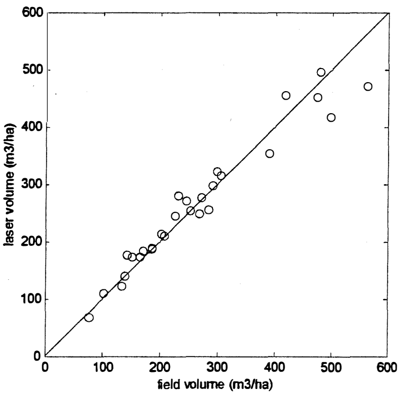

Figure 5. Estimated stem volume plotted against field measured stem volume for 29 forest stands each with the size 0.64 ha.

The relative RMSE for mean tree height, basal area, and stem volume estimations was similar for the four different measurement densities (0.1 to 4.3 laser measurements per m2). Paired t-tests were used to test whether there was a difference between the absolute value of the difference between laser predicted and field measured values for the reduced and the non-reduced laser measurement densities. There was no significant difference ($p < 0.05$) when using the lowest measurement density compared with using the highest measurement density for estimation of tree height and stem volume.

DISCUSSION AND CONCLUSIONS

The underestimation of field measured tree height found in the first study is in agreement with other studies. The fact that the extractor algorithm used in the first study only detects the four first peaks in the return have to some extent increased the underestimation of tree heights. The underestimation is probably also a result of laser beams that hit at the side of the conical tree crowns, rather than hitting close to tree tops. Aldred and Bonnor (1985) showed that laser measured stand heights for both hardwoods and softwoods underestimated field measured stand heights by 2.8 to 3.1 m. In the first study, features of the returned waveform were found to be most useful for estimation of stem volume. The ratio between number of returned pulses from the vegetation and the number total number of returned pulses was not included in the final regression model for estimation of stem volume. This ratio was found to be useful for stem volume estimations in the second study as well as in other studies (e.g., Næsset 2002).

The estimation accuracies obtained for mean tree height, basal area, and stem volume at a stand level were similar to what was obtained by Næsset (2002) who predicted the same variables in similar forest types. It should be noted that the empirical derived relationships between laser variables and forest variables could be forest type dependent (Nelson, 1997).

An important finding in both studies was that the sampling density could be reduced to a certain degree without any significant decrease in prediction accuracy for stem volume and tree height. The possibility to reduce the sampling density will make the laser data acquisition more cost effective.

Both studies show that reliable estimations of tree height and stem volume can be obtained at plot and stand level. However, the methods used were different because different laser scanning systems were used. In the first study the full waveform was available as opposed to the second study. Commercial airborne laser scanners operated today have been developed for terrain mapping and usually do not digitize the full returned waveform. The possibility to use the full returned pulse to achieve estimates of forest variables should be further investigated.

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MEASURING BIOMASS AND CARBON IN DELAWARE USING AN AIRBORNE PROFILING LIDAR

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ABSTRACT

A portable, inexpensive profiling lidar was used to inventory forests in Delaware, a small state (5,205 km^2) on the mid-Atlantic seaboard of the US. Ground and airborne sampling procedures are described, and large-area inventory results are reported and compared to independent estimates. Systematic airborne lidar profiling measurements were used (1) to estimate forest merchantable volume, biomass, and above-ground carbon state-wide; and (2) to estimate impervious surface and open water area. Over 1300 km of laser profiling data acquired along parallel flight lines 4 km apart were analyzed. In the best models, merchantable volume estimates were within 10% of US Forest Service estimates at the county level and within 1% state-wide. Total above-ground dry biomass estimates were within 19% of USFS estimates at the county level and within 16% state-wide. Lidar estimates of percent impervious area surface for the three counties - Newcastle, Kent, and Sussex - were 11.02, 3.35, and 2.82% respectively, and 4.75% state-wide. Comparable estimates developed using 30m Enhanced Thematic Mapper digital data and mixture modelling were 8.76, 3.50, and 3.88% respectively, and 4.90% state-wide. Laser estimates of open water at the county and state level were comparable to 1997 GIS estimates. Open water estimates based on laser transect data showed the 3 counties to have 2.80, 1.97, and 4.61% of their county area covered by water, and 3.43% of the state covered by open water. Comparable 1997 GIS estimates were 2.62, 2.07, 4.79% (county), and 3.51% (state), respectively. The results of the study indicate that Line Intercept Sampling techniques can be used in conjunction with a relatively inexpensive, portable airborne laser system to assess multiple resources regionally.

INTRODUCTION

Forward-thinking, progressive, environmentally and ecologically responsible nations of the world have adopted the Kyoto protocols in order to inventory, to monitor, and, ultimately, to reduce carbon emissions to mitigate global climate change. In support of these efforts, efficient sampling procedures need to be developed to periodically inventory standing carbon regionally on a timely basis. To this end, an investigation was undertaken to develop the hardware, software, and statistical framework to inventory above-ground forest biomass and carbon remotely. An inexpensive, portable airborne laser system was built from off-the-shelf components (Nelson et al., 2003a) and used to inventory the standing forest biomass and carbon of Delaware, located on the mid-Atlantic seaboard of the eastern United States. The State covers 5,205 km^2; it's dimensions are approximately 150 km N-S, approximately 55 km E-W near the southern end, and approximately 16 km E-W near its northern border. Line Intercept Sampling techniques were employed to convert the systematic, linear airborne laser profiling measurements of forest height, height variability, and canopy closure to estimates of merchantable volume, total above-ground dry biomass, and carbon. In addition, the same laser measurements were employed to estimate impervious surface area and open water area.

METHODS

Study Area

Three counties comprise the state - Newcastle, Kent, and Sussex. Newcastle County, northernmost of the three and encompassing 1124 km^2, is largely urban and suburban, with rolling topography which ranges from sea level to 137 m above MSL at the Pennsylvania line at the northern tip of the state (http://www.udel.edu/dgs/Publications/pubsonline/info8.html). Kent County (1542 km^2) and the southernmost county, Sussex (2539 km^2), have a larger agricultural base; the topography is essentially flat. Slightly less than one third of the State is forested, and forest area is distributed fairly evenly across the counties in small, dissected parcels. The state supports coniferous, deciduous, and mixedwood stands. Predominant conifer species include loblolly pine (*Pinus taeda L.*) and Virginia pine (*Pinus viginiana Mill.*). The major deciduous species in terms of frequency of occurrence include sweetgum (*Liquidambar styraciflua L.*), black gum (*Nyssa sylvatica Marsh.*), various oaks (*Quercus spp.*), hickories (*Carya spp.*), yellow poplar (tulip poplar or tulip tree, *Liriodendron tulipifera L.*), and red maple (*Acer rubrum L.*).

The University of Delaware (http://www.udel.edu/FREC/spatlab) provided the digital map used to stratify the state into eight general land cover types - conifer, mixedwood, hardwood (i.e., deciduous), wetlands, agriculture, residential, urban/barren, and water. 1992 color-infrared airphotos were used to build the initial GIS, which was updated in 1997 using B&W aerial photography.

Airborne Laser Profiler

A small, portable, first-return airborne laser profiling system was built using off-the-shelf components. The system consists of a 2000 hz laser transmitter/receiver, a CCD video camera, a video titler, and video recorder, a differential GPS system, and a laptop computer. The entire system, called PALS (Portable Airborne Laser System) cost approximately $30,000 USD in 1999. The entire system fits in two suitcases, and is designed to be bolted onto/into local for-hire aircraft. Generic components, compact size, portability, and low cost drove system design. The system is described in full in Nelson et al. (2003a).

PALS was used to collect ranging data (Figure 1) on 1306 km of systematically located flight transects during the summer of 2000. The State's long axis is oriented N-S; 14 flight lines were oriented parallel to the western boundary of the state every 4 km. Individual data collection runs ranged from 3 to 163 km. At 50m/s (180 kph) in a Bell 206 Jet Ranger, the longest flight transects took approximately 1 hour to complete. With turns, a 5 km run-up at the start of each line, and transit time to/from airports, 2 flight lines could be measured within the safe operational fuel limits of the helicopter. The 1300 km of flight transect data were acquired in less than two days at a cost of $6000 USD.

The laser transmitter operates at 2000 hz. A LabVIEW front end was written to collect the laser serial stream - range and amplitude - and the differential GPS serial stream. Only one of every 10 pulses was recorded, no pulse averaging was done. At a nominal flying height above ground of 150m and a laser transmitter beam divergence of 2.0 mr, the laser spot size at target was 30 cm. At 50m/s, the system recorded a laser pulse every 0.25 m along the flight transect. Post-processing was done to identify the ground line beneath the forest canopy, thereby facilitating the calculation of tree heights and canopy density from the first-return laser ranges.

Line Intercept Sampling

142 - 40 m ground transects were located and measured in 7 of the 8 strata state-wide (open water was not sampled). All trees whose crowns were intercepted by a plane vertically projected from the randomly oriented 40m transect were sampled. Sample tree location, i.e., distance along and across track, dbh, total height, merchantable height (10cm top), height to maximum crown diameter, and crown radius were noted.

The ground data were used to estimate merchantable volume and total above-ground dry biomass per hectare on each transect, as follows:

$$\hat{b} = \frac{10,000}{l}\left(\sum_{i=1}^{n}\frac{b_i}{c_i}\right)$$

where $\hat{b}$ is estimated biomass per hectare on a given sample transect, n is the number of trees sampled along the ground transect of length l, i.e., 40m, b_i is the biomass of tree i, and c_i is the crown diameter, i.e., twice the crown radius, of tree i, $i, i=1,n$ (Kaiser 1983; DeVries 1986). These same ground data were used to develop a canopy height model (CHM) for the ground transect. The CHM simulated what the airborne laser profiler would have measured had it flown over the top of the forest canopy directly above the 40m ground transect (Nelson 1997). Regression models were then developed which predicted ground-measured biomass (or volume) as a function of simulated laser measurements.

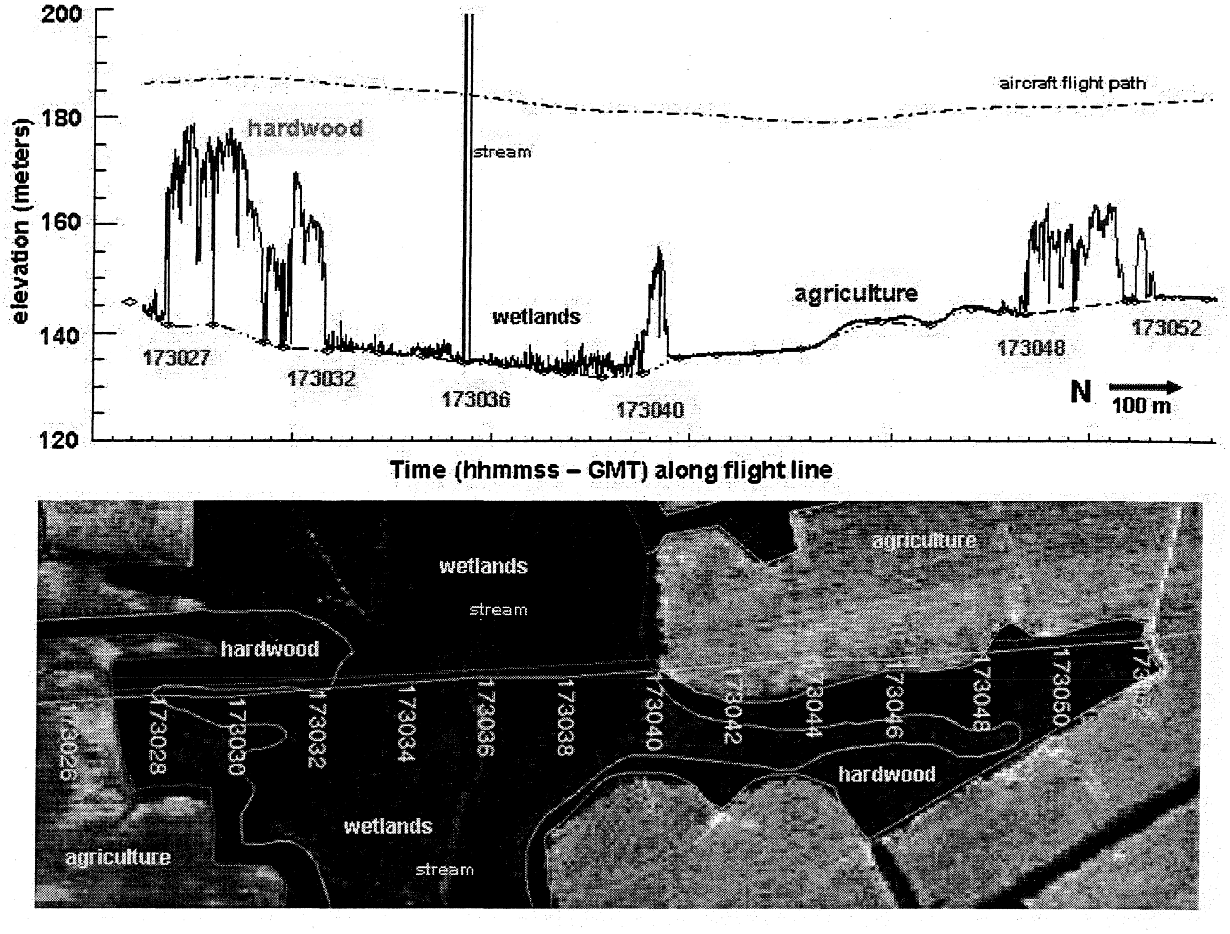

Figure 1. A 1.4 km section of a PALS flight line acquired over Delaware during June of 2000. The dotted line above the laser trace describes the aircraft flight path above mean sea level; that line is negatively offset to fit the flight profile onto the canopy trace. The nominal flight altitude was 150m AGL (above ground level). A 1992 color infrared photo (archived by the Spatial Analysis Laboratory, University of Delaware) of the flight segment is shown below the laser trace. GMT times (hhmmss) are posted along the actual flight line; each two second interval represents approximately 100m on the ground. The faint blue line just above the actual flight line (yellow) marks the planned flight path.

Stratified sampling was employed to convert the airborne laser profiles into stratum, county, and state estimates of volume and biomass. Each of the 14 flight lines was registered to the University of Delaware GIS to assign a stratum identity to every laser pulse. The airborne laser flight transects were partitioned into 40m segments, and laser measures of height, canopy height variability, and canopy closure were used as independent variables in the stratum-specific volume and biomass equations. Predicted volume and biomass were tallied by stratum and county. Segments less than 40m were considered and weighted appropriately in situations where the airborne laser profile crossed stratum, county, or state boundaries. In the following discussion, b refers to biomass/ha, calculated using the predictive equations, w is a weight, and the subscripts i, j, and k are county, stratum, and segment subscripts, respectively. b_{ijk}, for instance, is the estimate of biomass per hectare calculated using the airborne laser measurements on the k^{th} segment in the j^{th} stratum in the i^{th} county. n_{ij} is the number of airborne laser segments which transected the j^{th} stratum in the i^{th} county. a_{ij} refers to the area of stratum j in county i; a_i are the county areas, and a is the state area. In this Delaware study, there were 8 strata and 3 counties.

Stratum Estimates within County:

mean, biomass/ha:

$$\hat{\bar{b}}_{ij} = \frac{\sum_{k=1}^{n_{ij}} (w_{ijk})(b_{ijk})}{\sum_{k=1}^{n_{ij}} w_{ijk}} = \sum_{k=1}^{n_{ij}} (w_{ijk})(b_{ijk})$$

where $w_{ijk} = \frac{l_{ijk}}{\sum_{k=1}^{n_{ij}} l_{ijk}}$ and $\sum_{k=1}^{n_{ij}} w_{ijk} = 1$ [DeVries 1986, eqn. 22b, pg. 255]

variance:

$$\hat{\text{var}}\left(\hat{\bar{b}}_{ij}\right) = \frac{s^2}{n_{ij}} = \frac{\sum_{k=1}^{n_{ij}} \left(w_{ijk}^2\right)\left(b_{ijk} - \hat{\bar{b}}_{ij}\right)^2}{\left(n_{ij} - 1\right)\sum_{k=1}^{n_{ij}} \left(w_{ijk}^2\right)}$$

95% confidence limits: $\hat{\bar{b}}_{ij} \pm t_{n_{ij}-1}^{0.975} \sqrt{\hat{\text{var}}\left(\hat{\bar{b}}_{ij}\right)}$ [DeVries 1986, eqn. 24, page 256]

County Estimates within State:

mean, biomass/ha:

$$\hat{\bar{b}}_i = \sum_{j=1}^{8} (w_{ij})\left(\hat{\bar{b}}_{ij}\right)$$

where

$$w_{ij} = {a_{ij}}/{a_i} \quad and \quad \sum_{j=1}^{8} w_{ij} = 1$$

variance:

$$\hat{\text{var}}\left(\hat{\bar{b}}_i\right) = \sum_{j=1}^{8} \left(w_{ij}^2\right)\left(\hat{\text{var}}\left(\hat{\bar{b}}_{ij}\right)\right)$$

State Estimates:

mean, biomass/ha:

$$\hat{\bar{b}} = \sum_{i=1}^{3} (w_i)\left(\hat{\bar{b}}_i\right)$$

where:

$$w_i = {a_i}/{a} \quad and \quad \sum_{i=1}^{3} w_i = 1$$

variance:

$$\hat{\text{var}}\left(\hat{\bar{b}}\right) = \sum_{i=1}^{3} \left(w_i^2\right)\left(\hat{\text{var}}\left(\hat{\bar{b}}_i\right)\right)$$

LIS techniques were employed to estimate impervious surface and open water area. The PALS video record was used to document start and stop points in the airborne laser data stream where the flight transects crossed impervious surface or open water. Roof crossings, asphalt/concrete crossings, and water crossings were noted. Stratum, county, and state estimates of roof, asphalt/concrete, and water were developed as simple ratios. For instance, the percentage of area under roof in Kent County was calculated by dividing the total length of transects flown over rooftops in Kent County by the total length of transects flown over Kent County.

Of all of the work done in this project, this documentation of impervious surface and open water crossings was most time consuming. Although simple, the work was labor-intensive. The video record was matched with the laser profile and amplitude profile to identify specific pulses where the particular surface started and stopped. The minimum mapping unit, i.e., the minimum distance considered, was 1 m, about the width of a nominal residential sidewalk.

Accuracy Assessment

The forest inventory estimates were compared with U.S. Forest Service - Forest Inventory and Analysis (FIA) estimates of volume and biomass at the county and state level. The FIA is the US federal agency charged with measuring and monitoring forests nationally, by state, and by county within state. Prior to 2000, the USFS-FIA was mandated to provide decadal updates of the forest resources of each state. They inventoried Delaware forests by measuring 215 systematically located points in 1999. So as not to make allometry an issue, the same allometric equations employed by the FIA in Delaware (Scott 1979, 1981; Wharton and Griffith 1993) were employed in this study to estimate volume and biomass on the laser ground transects.

Laser profiling estimates of impervious surface area were compared with county and state estimates developed by Smith et al. (2003). They used sub-pixel mixture models to deconvolve impervious surface from porous materials in Landsat ETM 30m pixels.

Laser estimates of open water were compared with the University of Delaware GIS estimates of open water area (http://www.udel.edu/FREC/spatlab). Although this GIS was used to stratify the airborne laser data into eight different land cover types, it was not used or consulted as laser open-water distances were measured. Rather, the PALS video record was used to determine where along a given laser transect open water was intercepted. The University of Delaware GIS open water estimates, then, are used to validate the PALS open water estimates.

RESULTS

Numerous stratified and non-stratified linear and multiplicative models which related ground-measured volume and biomass to simulated laser measures were developed and cross-validated. Comparison of models developed for Delaware forests indicate that (1) considering all cover types collectively, stratification does not significantly improve accuracy; (2) considering conifer and hardwood models specifically, conifer volume and biomass predictions are significantly more accurate than hardwood estimates; (3) multiplicative models, e.g., $ln(biomass) = b_0 + b_1 (ln(height_{laser}))$, consistently fit better (i.e., have higher regression-R^2 values) but perform worse (i.e., have significantly lower cross-validation R^2) than explicitly linear models; and (4) explicitly linear models developed using standard least-squares techniques and nonparametric techniques - minimization of absolute error - produce the most accurate results. Based on these findings, laser-based estimates of merchantable volume and total above-ground dry biomass are developed using explicitly linear models. Laser-based estimates are compared with USFS-FIA estimates of volume and biomass, by county and state (Table 1). The FIA combines Kent and Newcastle County results to reduce standard errors of estimate in the smaller counties. Due to the ambiguous nature of the findings regarding the merits of stratification in this study and in studies done by others, both stratified and non-stratified results are considered. It must be noted that, due to differences between FIA - GIS cover type definitions and FIA - laser sampling methods, the FIA and laser estimates of volume or biomass are not directly comparable, i.e., one can not expect exact agreement. FIA timberland estimates for all Delaware tree species are compared with laser estimates for the four land cover classes considered forested in the University of Delaware GIS - hardwood, mixedwood, conifer, and wetlands.

Although it is certainly arguable as to which of these models is "best" due to the aforemen-tioned incompatibilities between FIA and laser estimates, the results in Table 1 indicate that laser- based transect sampling methods can be used to develop large area forest volume and biomass estimates. Laser-based merchantable volume estimates are consistently within 2 standard errors of the USFS-FIA estimates at the county and state level. Laser biomass estimates fall just

Table 1. Percent difference between USFS-FIA and airborne laser estimates total merchantable volume and total above-ground dry biomass, by county and state. Non-stratified and stratified results for Models 1 and 2 are compared to USFS-FIA estimates. Model 1 is parametric; model 2 is developed using nonparametric techniques.

dependent variable	*model*	*stratification*	***difference (%)****		
			New/Kent	***Sussex***	***Delaware***
Merchantable Volume	1	no	-23.5	-7.5 ‡	-14.4 ‡
		yes	-17.6 ‡	4.9 ‡	-4.8 ‡
	2	no	-9.6 ‡	7.7 ‡	0.3 ‡
		yes	-9.6 ‡	14.5 ‡	4.2 ‡
Total Above-Ground Dry Biomass	1	no	12.5 ‡	18.8	16.0
		yes	7.4 ‡	22.0	15.5
	2	no	15.7 ‡	22.7	19.6
		yes	8.3 ‡	21.1	15.4

* *[(FIA-laser)/FIA] x 100. Negative percentages indicate a laser overestimate.*

‡ *Laser estimate is within ±2 standard errors of the USFS-FIA estimate.*

outside the FIA 95% confidence bounds at the state level, this due to relatively large discrepancies between laser and FIA biomass estimates in Sussex County. The basis for this difference in Sussex County is unknown.

Per-hectare estimates of biomass developed using an explicitly linear, stratified, parametric model (Model 1 - stratified) are combined with areal estimates from the University of Delaware GIS to estimate state-wide carbon allocations, by land cover type and county (Table 2). A generic conversion factor of 0.5 is used to convert above-ground dry biomass to carbon (Gower et al. 1997; Houghton et al. 2000; Nelson et al. 2000, Table 2).

The importance of measuring carbon stores on land cover types that are typically considered "non-forest" is highlighted by the numbers presented in Table 2. State-wide, approximately 20% of the above-ground carbon resides on lands identified as agricultural, residential, and urban areas; half of that in residential areas alone. Approximately one-fourth of Newcastle County (24.3%), an urban/suburban county just south of Philadelphia and including the large city of Wilmington, is residential. That residential area collectively supports one-third of the County's above-ground carbon.

Although the primary reason for flying the laser flight lines over Delaware was to develop and test procedures associated with a laser-based, large-area forest inventory, it became apparent that the same data set could be used estimate the areas of a variety of land cover types, completely apart from those described by the Delaware GIS used to stratify the state. Line Intercept Sampling techniques were applied to all 1306 km of the airborne laser profiles acquired state-wide. Each pulse was identified as belonging to one of the following classes, based on pulse height, pulse return amplitude, and/or based on the video record - forest, nonforest, roof, asphalt/concrete, water. Any pulse which measured a target over 3m tall, not manmade, was considered a measurement of a tree. Nonforest pulses were those over natural targets less than 3m tall. [Note: 3m was used as a cut-off to prevent mature corn from being identified as forest. This cut-off is slightly less than the USFS definition of a tree - 12 feet, or 3.7m (Griffith and Widmann 2001).] Roof, asphalt, and concrete crossings were identified via the video record and aided by noting changes in the strength of the return laser signal. Water crossings were obvious in the laser profile since water generally absorbed the 0.905 μm, near-infrared laser pulse.

Forest, nonforest and open water estimates are compared with the University of Delaware GIS estimates. As in Table 1, there are, in Table 3, issues concerning comparison of estimates which are not exactly comparable. For instance, the laser survey defines a forest pulse based on height; the GIS photointerpreters define a wetland (considered a forested cover type) based on drainage and wetlands cover, not necessarily on the presence/absence of trees. Much of the GIS wetlands category is forested, but there are extensive areas along the Delaware Bay and Atlantic Ocean that support marsh grasses and which are devoid of trees. Also, whereas the laser sample separates impervious surfaces from pervious forest and nonforest, the GIS does not. So some unknown proportion of the GIS forest and nonforest polygons are, in fact, impervious. Despite these differences, GIS and laser estimates of forest area agree within 9% at the county level and within 4% for the State. Nonforest differences are within 5% for counties and within 1% for the State, with the exception of Newcastle County, the most urban of the three counties, where the difference is less than 12%.

Table 2. Airborne LiDAR profiling estimates of above-ground carbon, in thousands of metric tons, by land cover, county, and for the entire state. SEE=standard error of estimate.

	m	Newcastle	Kent	Sussex	Delaware
Hardwood		1592.8	736.7	186.5	2515.9
	SEE	26.5	16.7	9.0	32.6
Mixedwood		48.1	467.5	2047.8	2563.5
	SEE	2.7	5.1	13.6	14.8
Conifer		20.0	62.8	658.2	741.1
	SEE	1.6	2.5	9.9	10.3
Wetlands		346.9	1404.6	2050.6	3802.1
	SEE	18.2	29.7	31.7	47.0
	Forestland	2007.8	2671.7	4942.9	9622.4
	SEE	32.3	34.6	37.1	60.4
Agriculture		184.8	320.3	478.7	984.4
	SEE	10.4	15.0	17.4	25.4
Residential		636.0	229.9	453.2	1319.1
	SEE	20.0	10.3	13.7	26.5
Urban		189.0	36.5	102.1	327.6
	SEE	14.2	3.9	7.4	16.5
	Nonforest	1009.9	586.5	1034.4	2630.5
	SEE	26.7	18.7	23.3	40.6
	Water	19.6	5.4	11.9	36.9
	SEE	4.3	1.2	1.9	4.9
	Total:	**3037.4**	**3263.6**	**5989.4**	**12290.0**
	SEE	42.2	39.3	44.4	72.9

Open water estimates should be directly comparable, though the minimum mapping unit (mmu) for the laser was much smaller (1m transect crossing length) than the mmu of the photointerpreters (4 acres, or 1.62ha). Laser and GIS open water estimates differ by ≤0.2% at the county and state levels.

Total impervious surface area is compared with estimates developed by Smith et al (2003). They used a mixture model to parse each 30m Thematic Mapper pixel into impervious and pervious surface percentages. Impervious surfaces are non-point pollution sources, and monitoring impervious surface area is important from a pollution monitoring and mitigation standpoint. Satellite mixture model estimates and airborne laser profiling estimates agree within 2.3% at the county level and within 0.2% at the state level.

Table 3. Forest, nonforest, impervious surface, and open water estimates based on airborne laser profiling data (from Nelson et al. 2003b, Table 2). Independent estimates are provided for comparison directly below the laser table. SEE = standard error of estimate. Percentages may be converted to area by multiplying the table entries by the following areas: Newcastle - 112412 ha, Kent - 154234 ha, Sussex - 253896 ha, Delaware - 520543 ha.

	Laser Profiling Estimates of Land Cover (%)			
	Newcastle	Kent	Sussex	Delaware
Forest	27.92	26.85	33.66	30.40
SEE	0.71	0.50	0.39	0.31
Nonforest	58.26	67.83	58.92	61.42
SEE	0.58	0.53	0.37	0.28
Pervious Surface	86.18	94.68	92.58	91.82
SEE	0.25	0.39	0.24	0.13
Roof	3.45	1.13	1.04	1.59
SEE	0.05	0.08	0.06	0.02
Asphalt/Concrete	7.57	2.21	1.77	3.16
SEE	0.11	0.12	0.09	0.05
Impervious Surface	11.02	3.35	2.82	4.75
SEE	0.15	0.15	0.12	0.06
Water	2.80	1.97	4.61	3.43
SEE	0.21	0.37	0.22	0.12
TOTAL:	100	100	100	100

	Independent Estimates of Land Cover (%)				
	Newcastle	Kent	Sussex	Delaware	Source*
Forest	27.60	35.64	36.04	34.10	UD-GIS
Nonforest	69.78	62.29	59.18	62.39	UD-GIS
Impervious Surface	8.76	3.50	3.88	4.90	Smith
Open Water	2.62	2.07	4.79	3.51	UD-GIS

** The University of Delaware GIS (UD-GIS) land cover percentages total to 100%.*

CONCLUSIONS

A statistical framework has been developed and tested whereby systematic, airborne LiDAR profiling measurements of forest canopy height, height variability, and crown closure are converted into estimates of forest merchantable volume, total above-ground dry biomass, and above-ground carbon. Using stratified, linear parametric and nonparametric models, laser-based estimates of merchantable volume differed from U.S. Forest Service-Forest Inventory and Analysis estimates by less than 5% state-wide and by less than 18% at the county level. Biomass estimates differed by ≤16% at the state level and ≤22% at the county level. Certainly the agreement isn't perfect, nor is perfect agreement a reasonable expectation given differences in land cover definitions and sampling procedures The USFS-FIA estimates are based on 215 systematically sampled plot clusters which are post-stratified based on tree species encountered on the plots. The laser inventory is based on (1) 142 - 40m ground sample transects used to develop the regression relationships used to calculate volume and biomass, (2) a photointerpreted land cover map comprised of eight general land cover types (e.g., hardwood, mixedwood, conifer, wetlands); and (3) 1306 km of flight data. Though final judgement of the goodness of agreement is left to the reader, the authors are encouraged by the level of agreement between the two disparate inventory techniques.

Dry biomass estimates were converted to above-ground carbon estimates by using a generic multiplier of 0.5 t C/1 t dry biomass, and tallied by stratum, county, and for the State. The itemized carbon allocation for Delaware (Table 2) is provided as an example of the type of detail that can be extracted from airborne laser profiling data. The carbon table also highlights the importance of residential and urban areas with respect to C stores in developed areas.

The results also support the fact that an airborne laser profiler can be used to estimate the areal extent of forest, nonforest, impervious surface area, and open water area. Impervious surface area can be divided into area under roof and area under concrete or asphalt based on the height characteristics of the surface.

PALS was designed to inventory large forested areas in out-of-the-way places, places such as the Amazon, the Congo, Madagascar, and the circum-polar boreal forests where relatively little is known about biomass and carbon stores. It is a sampling tool, and it is best applied in situations where repeated measures of forest structure (i.e., height, height variability, canopy closure), forest volume, biomass, and carbon are needed across large areas - 10's or 100's of thousands of square kilometers. The laser system is designed to be small, robust, transportable, and (relatively) easily integrated onto local, for-hire aircraft. It is not wedded to a specific type of aircraft, rather it is meant to be flown on a variety of small planes or helicopters. At this point, the system has been used on a Bell 206 JetRanger, a UH-1 "Huey", and a Twin Otter. It's nominal operational envelope is 150 - 300m above terrain.

Future work will involve efforts in a number of different areas with the overall objective being to develop an on-the-fly, laser-based, airborne forest inventory system which can be flown on many different types of small aircraft. Research areas include the following:

1. Improve regressions used to predict volume and biomass. Though not discussed in this report, some of the predictive equations, most notably the hardwood equations, were weak, with R^2 values occasionally less than 0.5. We believe that longer field transects, on the order of 100m, need to be considered in order to improve regression fits. Natural variation in the Delaware forests is high and highly influential observations common. Future studies will key on the use of nonparametric techniques to develop the explicitly linear, predictive equations in order to mitigate the effects of outliers.

2. Develop the flight hardware needed to fly PALS on other types of aircraft (e.g., Cessna's).

3. Replace the first-return laser transmitter/receiver with a first/last return transmitter to facilitate identification of ground beneath canopy.

4. Develop automatic ground-finding and roof-finding algorithms so that the laser data stream can be processed in-flight. If heights can be reliably measured and if roofs can be automatically excluded, then an airborne laser profiling system can be flown such that the laser and GPS data are stored and simultaneously processed to tally volume, biomass and carbon on-the-fly. Automated ground and roof finding algorithms have been developed and will be improved. It is realistic to ex-

pect that, in just a few years, airborne laser profiling systems will be flown such that the volume, biomass, and carbon inventory is done when the aircraft touches down.

Without doubt, the future of airborne laser remote sensing belongs to airborne and spaceborne laser scanners, not to airborne profilers. Currently, however, laser scanning systems are expensive and the data streams are dense. Profilers offer technical simplicity, transportability, and a manageable data stream that allow researchers to consider processing real-time in remote areas. They also duplicate, at a much finer spatial scale, the data acquisition attributes of spaceborne laser profilers currently flying (the Geosciences Laser Altimeter System - GLAS, aboard the Ice, Clouds, and Land Elevation Satellite - ICESat) and proposed multi-beam profilers (the Vegetation Canopy LiDAR - VCL). The use of an airborne laser profiler such as PALS should be considered in situations where volume, biomass, and carbon need to be repeatedly measured over large, remote regions where little or no forest inventory information exists. The results of this study provide a quantitative assessment of the estimation accuracy which might be expected from an airborne laser profiler.

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LASER SCANNING AS A METHOD OF FOREST INVENTORY: ESTIMATION OF FIRST EXPERIENCE.

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ABSTRACT

The main purpose of this paper is to estimate and evaluate latest experiments in laser scanning of covered by forestlands and make some outline of it possible implementation in the future. Laser scanning of Earth surface may be considered now as a promising new technology of geomatics and should be estimated from forest inventory point of view. Experiments with laser scanning of forest land were done from helicopter MI-8 (or plane AN-2) using standard mapping laser ALTM-1020 (Optech Inc.), which works as scanning distance measurer with frequency 5000-20000 impulses per second, flight velocity – 200 km/hour, height – 200-400 meters. The wide of scanning strip depends on scanning angle and height. Scanning was adjoined by determination of coordinates of all detected objects using system of ground based and flying GPS receivers Ashtech Z-12 (Ashtech Z-Field Surveyor and Ashtech Z-Surveyor) which allows to determine coordinates of the ground objects with precision 15-20 cm and construct the surface digital model. The scanned data after was treated with ALTEX Observer software in interactive regime. Primary treated data is possible to transfer in such well-known GIS systems as ARCINFO, MAPINFO, ERDAS Imagine etc. The forest inventory parameters such as tree stands growing stock, mean diameters and heights, leaf index etc. may be measured directly or calculated using data on diameters of tree crowns, stem diameters, tree heights. Estimated error of measurements was checked using ground inventory of scanned areas and it not exceed 10%. So, laser scanning covered by forestlands for forest inventory purposes seems to be one of the most promising new methods to conduct forest measurements.

INTRODUCTION

In Russia (at that time Soviet Union) laser methods, directed toward forest resources' survey had been developed before onboard aircraft and satellite lasers appear. There are mainly investigations which had been done at Leningrad Forestry Research Institute (LenNIILH) by V.I. Solodukhin with coauthors, who demonstrated high efficiency of forest laser profiling combined with traditional (classic) aerial photography for timber cruising purpose [Solodukhin et al. 1977, 1985; Stolyarov et al. 1987].

In North America (Danilin, Medvedev, 2001) laser mapping methods using satellite and aircraft platforms was developed and widely practiced at geodesy, cartography and forest inventory and survey [Aldred et al. 1985; Krabill et al.1987; Chappelle et al.1989; Kalshoven et al. 1990; Ritchie et al.1993; Weltz et al.1994; Blair et al.1996; Lefsky 1997; Ackermann 1999; Means et al. 1999, 2000, 2001; Magnussen et al. 2000; Dubayah et al. 2000].

During last years with appearance and availability of satellite positioning and navigation systems (US GPS and Russian GLONASS), satellite and aerial laser scanning and digital video- and photography, new possibilities appears for remote sensing of terrestrial ecosystems and forest cover with highly accurate measuring relief and heights of ground objects at about ±10-15 cm and positioning of their space coordinates at about ±15-20 cm and higher accuracy [Ritchie et al. 1993; Sweda et al. 1998; Danilin et al. 1999, 2000, 2001, 2002; Medvedev 2000].

Experiments on laser scanning of covered by forest lands to examine will it be the proper method for forest inventory were done in Siberia together by Laboratory of Forest Inventory and Forest Planning, V.N. Sukachev Institute of Forest of Russian Academy of Sciences and Opten Limited.

METHODS

This section mainly follows the paper (Danilin, Medvedev, 2001). Aerial survey is made from Mil-8 helicopter by laser scanning set ALTM 1020 by Optech Inc., Canada. Video and photo scenes are recorded simultaneously by Sony DCR-PC110 megapixel mini DV camcorder with Carl Zeiss Vario-Sonar optics and KODAK DSC-EOC 1c digital camera with 3000×2000 pixel resolution CCD which provides 10 cm high on ground linear resolution from 300 m of flight altitude at about 300 m of scanning path width [Opten's 2001, Danilin et al. 2000].

The width of the patch covered in a single pass of aircraft depends on the scan angle of the laser system and the aircraft flight height. Typically operating specifications are at flying speeds of 200 to 250 kilometers per hour (55-70 meters per second), flying heights of 300 to 3,000 meters, scan angles from 0 up to 20 degrees, and pulse rates of 2,000 to 25,000 pulses per second. These parameters can be selected to yield a measurement point every few meters, with a footprint of 10 to 15 centimeters, providing enough information to create a digital terrain (DTM) and forest vegetation model adequate for many forestry and forest engineering applications, including the design of forestry operations, projecting and alignment of forest roads, the determination of timber stock and volumes of ground works, and the design of harvesting schemes and structures.

The position of the aircraft at the time of each measurement is determined by phase difference kinematic Global Positioning System (GPS). Airborne and ground based GPS receivers Ashtech Z-12, Ashtech Z-Field Surveyor, Ashtech Z-Surveyor are used for the laser airborne survey. Rotational positions of the beam director are combined with aircraft roll, pitch and heading values determined with an inertial navigation system, and the range measurements to obtain vectors from the aircraft to the ground points. When these vectors are added to the aircraft locations they yield accurate coordinates of points on the surface of the terrain. Uncertainty of one-time measurement of geographical coordinates using ALTM-1020 machine and Ashtech GPS does not exceed 0.1% of flight height (Basic 2001).

General scheme of airborne laser terrain mapping system had been used for inventory of forest lands is shown at figure 1.

Laser sensing data and digital video images and photographs are examining for quality and pre-processing at once on board of aircraft and later on ground using special software which allow to get geometric parameters and highly accurate coordinates of separate trees and well readable morph structural characteristics of forest canopy along the flight course.

All images and database are presented at three dimensional (3D) view as customers may work with digital terrain model (DTM) and video- and photographs at more comfortable regime.

At 2000 general methodology of forest cover mapping and stand structure interpreting by ALTM-1020 machine was studied and developed. The research had been placed along 200 km flight and sampling transect at Turukhansk region of Krasnoyarsk krai, Central Siberia, within Bakhta river basin (right tributary of Yenisei river) (63-64°N, 91-92°E) at subzone of Siberian middle taiga dominated by larch (Larix sibirica) - spruce (Picea obovata) – Siberian pine (Pinus sibirica) forests in some sites mixed with birch (Betula pendula) and sphagnum bogs and wetlands.

For ground verification of aerial survey data 35 sample plots were established along the transect representing all dominating forest types and site environments. At the sample plots sample trees were selected, measured and cut down by 2 cm DBH and 1 m height range for stem analysis and stand phytomass assessment.

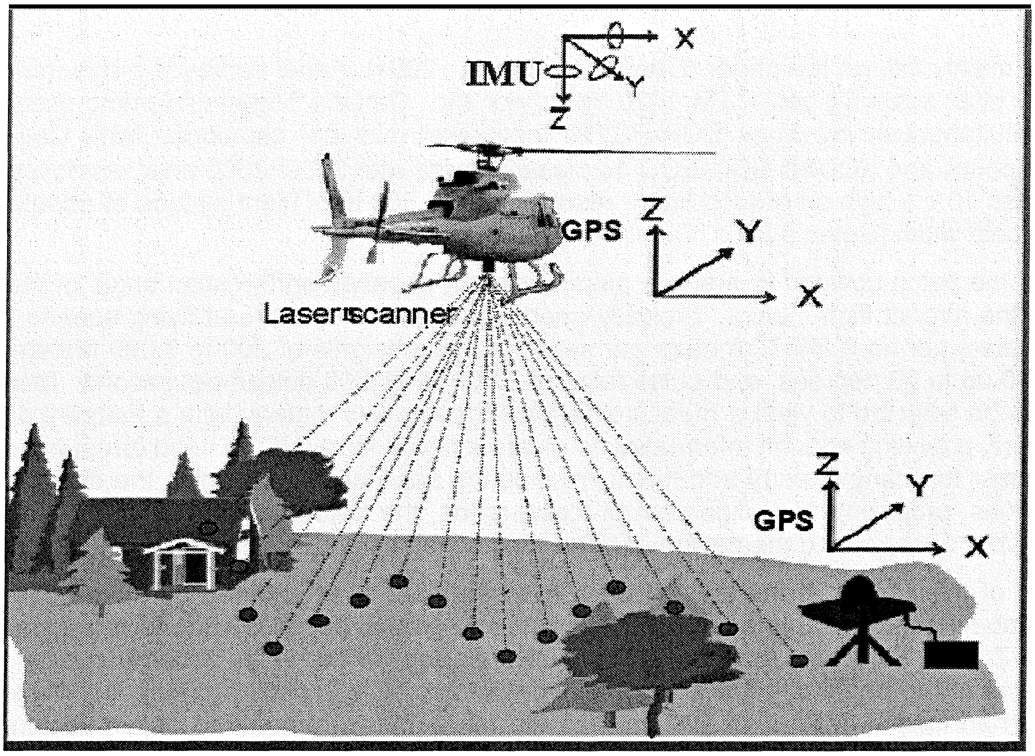

Figure. 1. General scheme of airborne laser terrain mapping system.

Interactive processing of laser and digital photo data is implemented by original Altex Observer software [Altex 1999] which is intended for use on IBM-compatible computers and provides the following capabilities:

- Visualization of primary data of laser location survey and results of their topological processing in user-defined scale and aspect.
- Data separation into true terrain geometry, vegetation, manmade objects and structures with a possibility of their individual visualization.
- Visualization of digital aerial photos of the route draped on laser data.
- Displaying of digital or raster topographical map and marking location of the surveyed object.
- Defining of space and altitude geodetic coordinates of any objects and areas.
- Available data sets (copy of screen)
- Creation and visualization of profiles and sections (putting of corridors and different projections).
- Computer-aided carrying-out of complex geometric measuring: calculation of distances between trees, between crowns and ground, between the trees and other objects marked by operator etc.
- Conducting of information-searching operations and data output with forming listing of critical vegetation zones (burnings, cuttings, silkworm forest damaged areas and others).
- Synthesizing of halftone shaded scene images with arbitrary selection of a lighting source.
- Tuning export of data to any software for their specialized post processing such as AutoCAD, PLS-CADD, POLE-CAD, ArcView, ArcInfo, MapInfo, Erdas Imagine (Fig. 2).

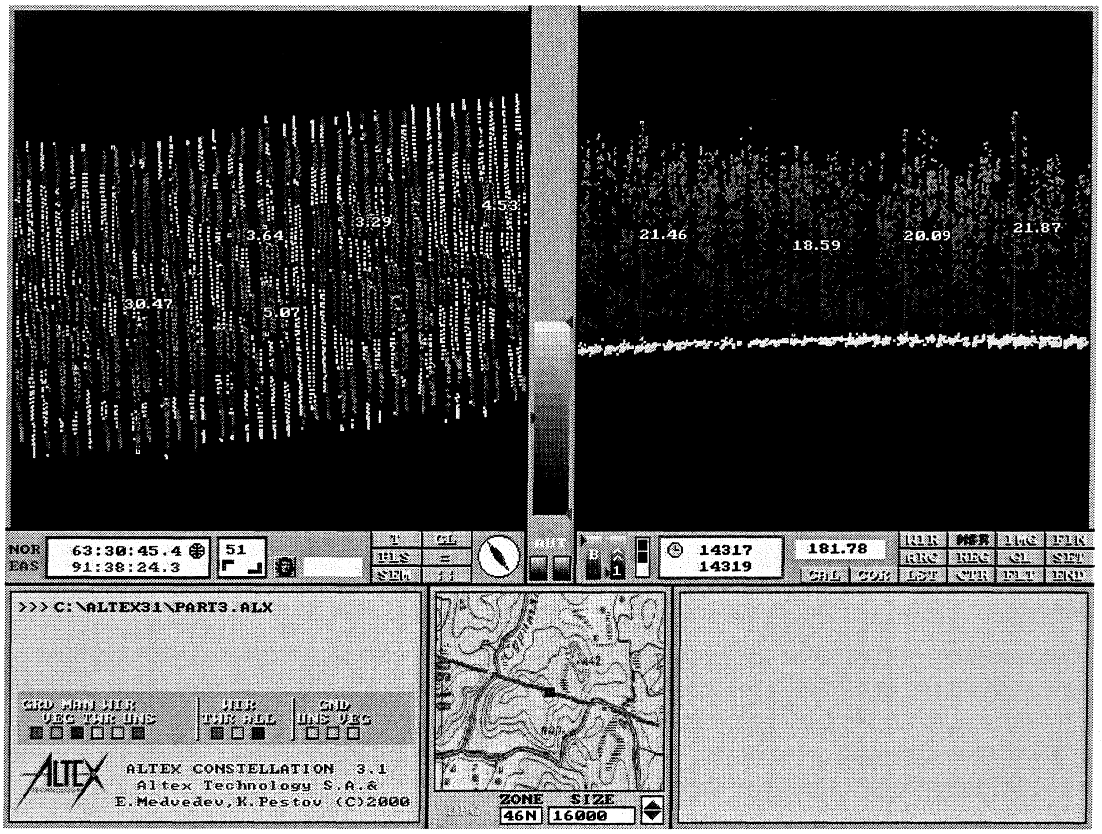

Figure 2. Visualization and complex geometric measurement of forest stand laser location data at Altex Observer working window.

Regression analysis of relationships between forest landscape relief shapes as it presented by the field of heights above sea level (altitudes) at the points with known from GPS determinations geographical coordinates and parameters of structure and productivity of forest cover was done (Usol'tcsev, 1998; Alekseev, Chernikhovsky, 2001).

Regression equation was used in following form:

$$y = a * H + b * S,$$

where *y*- parameter which describes the structural or productivity feature of forest cover such as share of conifers on covered by forest lands, share of broadleaf's on covered by forest lands, share of productive forest lands, growth class of forest lands, growing stock etc.

H – is the entropy of the field of heights.

$$H = -\sum_{i=1}^{n} p_i * \ln p_i ,$$

where p_i – is relative height of relief surface at point *I*,

$p_i = h_i / \sum_{i=1}^{n} h_i$, h_i – altitude at the point *I*, *n* – number of points at which estimation of altitude was done,

S – standard deviation of the field of heights.

$$S = \sqrt{\frac{\sum_{i=1}^{n}(h_i - h)^2}{n-1}},$$

here h – is mean height above sea level of forest landscape, $h = \frac{\sum_{i=1}^{n} h_i}{n}$.

Parameters H and S appears good describes the shape of relief of forest landscapes meanwhile last play key role in energy, water and nutrition's exchange in the forests ecosystems determining its structure and productivity.

Regression analysis was done for two sample areas Karelian Isthmus of Leningrad region and reserve "Verhne-Tazovsky" of Yamalo-Nenetsky autonomous district.

RESULTS

As a result of processing of the laser location data we get primary ground profile, which consist of vegetation and topographic (ground) surface profiles (Fig. 3a). Topographic surface is interpolated consequently by equalization and joining (unification) of points, where laser beam had reached the ground penetrating through tree crowns/leaves (Fig. 3b). Eliminating topographic profile from the primary one we get forest vegetation/tree stand profile (Fig. 3c).

The analysis of forest vegetation and tree stand structure integrated with aerial digital photographic and video data allow to accurate interpretation of different types and layers of forest vegetation dividing it by tree species, density and other parameters (Fig. 4).

The laser location survey method combined with high-resolution digital photography as well as on-ground and airborne GPS support allow remotely, operatively and with high accuracy to get information on forest cover condition and environment with a basic scope of data on surveyed object which may be a foundation for various thematic GIS compilations of different complexity.

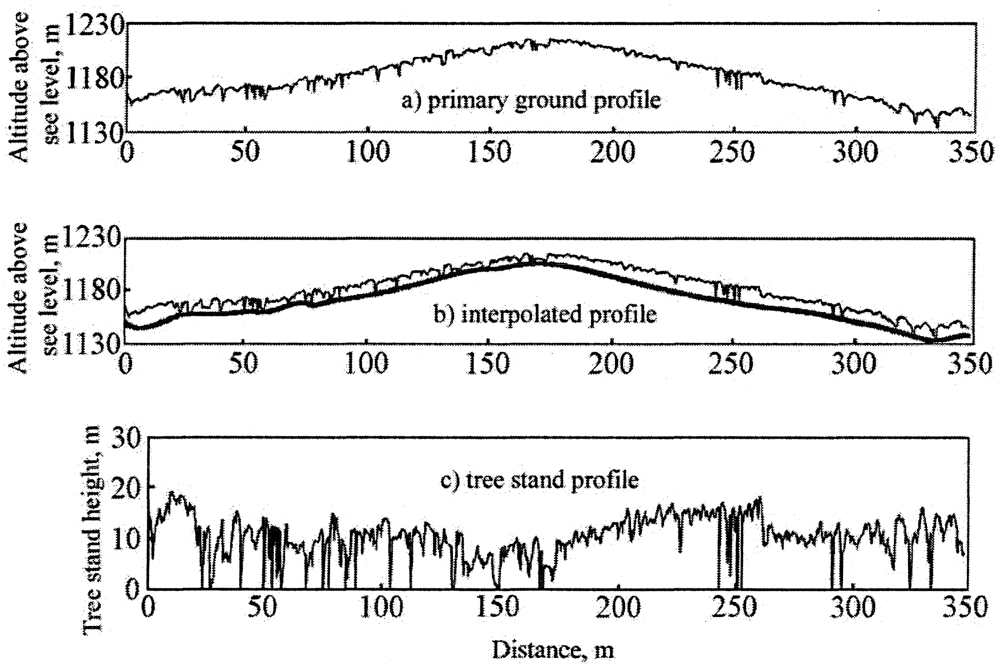

Figure 3. Main stages of processing of laser location data of forest vegetation profiles.

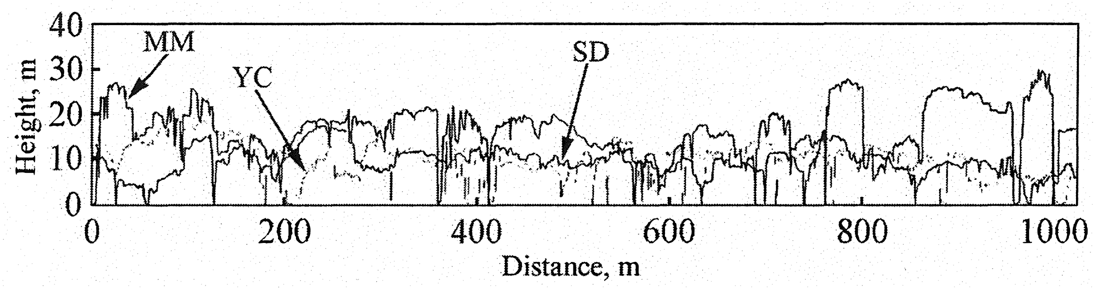

Figure 4. Integrated profile of tree stand: mixed mature (MM), young coniferous (YC) and secondary deciduous (SD) stands.

The laser location survey method combined with high-resolution digital photography as well as on-ground and airborne GPS support allow remotely, operatively and with high accuracy to get information on forest cover condition and environment with a basic scope of data on surveyed object which may be a foundation for various thematic GIS compilations of different complexity.

Comparison of remote and ground based data

To check the precision of remotely obtained data on growing stock volumes and above ground phytomass of tree stands the comparisons with the data from sample plots were done. The results are presented in table 1. (Danilin, Krasikov,2001).

For comparisons the data from 10 sample plots were used, Tree stands on sample plots are Larch dominated.

Deviation of sample plots and laser scanning data generally less than 10%.

Table1: Comparison of laser scanning data and the data from reference sample plots (Danilin, Krasikov, 2001)

№	Speices composition	Age, years	Site index	Mean		Σg, m^2/ha	Density, trees per hectare	Growing stock, m^3/ha		Deviation		Above ground phitomass, t/ha dry matter		Deviation	
				Height, m	diameter, cm			Sample plot data	Laser scanning data	m^3	%	Sample plot data	Laser scanning data	Tons	%
1	9Larch 1Spruce	250	IV	22.0	31.7	17.1	220	169	178	9	5.3	139.6	146.6	7.0	5.0
2	9Larch1Spruc e+Birch	130	IV	20.7	26.0	20.2	380	192	205	13	6.8	152.6	162.8	10.2	6.7
3	9Larch1Spruc e	160	III	23.0	28.6	30.0	470	307	303	-4	-1.3	253.8	251.3	-2.5	-1.0
4	9Larch1Cedar +Spruce, Birch	170	III	23.6	30.0	29.1	412	310	300	-10	-3.2	251.2	244.0	-7.2	-2.9
5	10Larch	100	IV	19.4	20.0	17.2	547	149	157	8	5.4	121.8	127.8	6.0	4.9
6	10Larch+Ced ar	260	IV	22.6	33.0	19.2	225	197	192	-5	-2.5	158.9	155.8	-3.1	-2.0
7	9Larch1Spruc e+Cedar	120	IV	20.2	24.2	18.9	418	170	173	3	1.8	141.9	144.0	2.1	1.5
8	10Larch + Cedar	210	IV	22.0	31.0	17.1	227	168	156	-12	-7.1	137.7	128.7	-9.0	-6.5
9	7Larch3Cedar + Spruce, Birch	200	III	24.0	30.0	27.9	395	295	306	11	3.7	244.9	253.0	8.1	3.3
10	9Larch1Cedar +Spruce	210	V	17.5	24.5	18.2	386	145	148	3	2.1	116.4	118.1	1.7	1.5

Results of regression analysis in the system "forest landscape relief shape - structure and productivity of forest cover".

Table 2 and 3 presents the results of regression analysis of relationships between forest landscape relief shapes and parameters of structure and productivity of forest cover for two sample areas.

Table 2: Results of regression analysis "forest landscape relief shape - structure and productivity of forest cover" for Karelian Isthmus of Leningrad region.

Structure or productivity of forest cover, *Y*	Parameters of regression equation *Y* =*a***H*+*b***S*		
	a	*b*	Coefficient of determina-tionR^2, %
Share of forest land dominated by Scots pine	8.8	2.6	93.2
Share of forest land covered by coni-fers	15.1	1.6	98.71
Share of forest land covered by broadleaf's	7.81	-1.55	85.17
Share of forest land dominated by birch	6.5	-1.22	84.54
Share of forest land covered by forest of bilberry type	17.44	-1.88	97.21
Mean growth class of birch stands	0.47	0.04	99.5

Table 3: Results of regression analysis "forest landscape relief shape - structure and productivity of forest cover" for reserve "Verhne-Tazovsky" of Yamalo-Nenetsky autonomous district.

Structure or productivity of forest cover, *Y*	Parameters of regression equation $Y = a*H + b*S$		
	a	*b*	Coefficient of determination R^2, %
Share of forest land covered by forest	15.69	0.9	99.05
Share of productive forest land	16.83	0.64	98.84
Share of forest land dominated by Scots pine	22.8	-2.1	91.62
Share of forest land covered by conifers	22.67	-0.51	99.07
Share of forest land covered by light conifers	23.09	-1.68	95.48
Share of forest land dominated by aspen	-0.24	0.08	42.3
Share of forest land covered by forest of Lichen type	13.19	-1.70	73.56
- Green mosses type	2.89	1.43	89.65
- Ledosum-Vacciniosum type	4.58	0.46	85.20
-Vacciniosum-Ledosum-Mosses type	-1.77	0.96	68.12
-Ledosum-Sphagnum type	3.27	-0.35	65.9
Biodiversity index (D-индекс)	0.40	0.05	87.72
Mean growth class of all species	1.17	-0.014	99.74
Mean growing stock of all species, m^3/ hectare	16.85	1.87	97.60

The data of table 2 and 3 shows us that structural features of forest cover which can't be determine by laser scanning alone may be estimated using above results of regression analysis. Needed for such analysis data on landscape relief may be obtained either from GPS work in parallel with laser or separately, from topographic maps.

Cost estimation

Only current expenses without needed investments was estimated both for laser scanning and traditional methods of inventory for Russian conditions. Cost of laser scanning was estimated using following parameters: flight height – 300 meters and scanning angle – 20 degrees results in scanning strip width 200 meters or scanned area 4000 hectares per hour. One our work of MI-8 cost approximately 1000 USD/hour, so current cost of laser scanning may be estimated as 0,25 USD/hectare.

Traditional forest inventory have the standard area, which should be inventoried by one person as 66 hectares/day. Taken into account mean salary 10 USD/day cost of traditional inventory may be estimated as 0,15 USD/hectare. So, still now traditional inventory more informative and cheaper. In the most probable future standard area will decrease but salary increase and general balance become more favorable for laser scanning as a method of forest inventory.

CONCLUSIONS

Estimation of possibilities to use laser scanning data for forest inventory and subsequent forest management shows that some needed for forest management parameters can't be estimated by laser scanning method alone. These parameters are species composition, age, site growth class, compartments borders within covered by forest land, forest type, regeneration, vitality class, wood quality class. So, now laser scanning method needs for support from some other methods of data obtaining or data treatment such as photo survey, video survey or preliminary regression analysis.

As a method of forest survey laser scanning has obvious merits such as

- High-tech new promising method with good perspectives for the future
- High precision in determining of height, diameters and density of trees
- All the data are obtained from very beginning in digital formats
- Possibility for creating of 3D digital terrain models as an additional result of scanning
- Possibility for tree level of forest inventory

Now main fields of application of laser scanning method in forestry may be forest inventory for the areas out of intensive forestry and forest industry, monitoring of forest lands, total biomass and carbon stock estimations, landscape analysis on the base of 3D terrain mapping.

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ASSESSING TREE HEIGHT AND STOCKING DENSITY FOR EVEN-AGED MATURE SPRUCE STANDS USING LIDAR AND DIGITAL AERIAL PHOTOGRAPHY

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ABSTRACT

Tree height and stocking density are two of the most important parameters for the estimation of standing volume in commercial forest plantations. However, field measurements may be labour intensive, spatially limited and not very representative if not carefully planned. In contrast, remote sensing methods are becoming a cost-effective alternative to field measurements because they provide: More rapid and frequent data acquisition, faster processing to deliver information, automated processing to deliver information, maps and information delivered at a much greater sampling intensity and maps of forest attributes below the stand level.

This paper will describe the work undertaken in two forest districts in Britain (Kielder Forest in the North of England and Aberfoyle, in the West of Scotland). The aim is of this project is the development of a method for the estimation of stocking density, standing volume, and the spatial distribution of number of trees and volume for forest planning purposes using a combination of digital aerial photography and airborne Lidar.

Lidar data were flown at an intensity of 4 returns per m^2. Digital aerial photography was collected at a ground resolution of 20x20 cm during the same flight. The flight dates were in September 2002 and March 2003 in order to avoid the start of the growing season.

Field work data for the validation of this analysis was undertaken at two scales. At the stand level, 12 plots of 50x50 metres each were sampled in each district, where stand parameters such as number of trees, dbh, dominance, top height, x-y location of each tree and forking, were collected. The location of each plot was established using a differential GPS and the location of individual trees was achieved using a field laser and transects starting from a well located point.

Inside each plot, 3 plots of 10x10 metres were randomly located, where tree data such as number of trees within the plot, the height and dbh of each one, crown diameter (n-s and e-w) and height to the first live whorl, were also collected. These small plots provided the data for the validation of remote sensing methods at tree level. In particular, crown dimensions and individual tree heights provided a good source of information for the validation of the Lidar data.

Parameters such as actual spacing, basal area, yield class, standing volume and stem volume were calculated later using standard procedures.

Data were analysed at two scales (tree and stand level) using a multi-resolution and object oriented image analysis in eCognition (Definiens, 2003). The automatic location of each tree was achieved using a segmentation method that aimed at the discrimination of tree tops based on reflectance and shape. The result of this analysis rendered image primitives that where further classified. This classification followed a rule-based system where Lidar and aerial photography data were combined to retrieve stand and trees properties. The method used a fuzzy classifier and properties were assigned to the stand and tree classes according to the degree of membership to each class. The link between the two working scales followed the hierarchical structure defined in an object-oriented analysis technique. This link will determine the applicability of the of current growth and yield models as they are normally affected by the level of homogeneity of the stands.

COMBINING LIDAR- AND GIS DATA FOR THE EXTRACTION OF FOREST INVENTORY PARAMETERS

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KEY WORDS: Lidar, laser, data fusion, forest inventory, FOGIS, tree delineation, tree species, pouring.

ABSTRACT

During the last decade the protection of nature has become a very important aspect for interference or structural alterations. It is necessary for all planning, which might have consequences for nature or impairments of nature, to get information about the actual state and the variations of landscape components. A promising field for the extraction of the needed information is the *lidar* (light detection an ranging) remote sensing technology. This technology provides vertical information of the land surface, especially of the vegetation.

In this approach the automatic extraction of information is based on the combined analysis of lidar- and GIS-data. The remote sensing system used consists of a lidar scanner and a RGB/NIR digital line camera. The laser scanner device is a discrete-return lidar device. It is able to record the first and last pulse of each foot print simultaneously. The main objective of the current project, called NATSCAN, is to determine basic variables for forest inventories such as *tree species, tree height* and *crown area.* These parameters are used to estimate further variables like *tree age, stem diameter, h/d-proportion, timber volume and tree species distribution.* In order to achieve the above main objectives three important tasks are the delineation of trees, the determination of the tree species and the delineation of stand units. The paper will focus on the automatic delineation of the tree crown shapes, the automatic recognition of forest stand units and the calculation of the mean tree height of the highest trees in each stand unit and the calculation of the crown cover density in each unit.

1. INTRODUCTION

One great aim of the project NATSCAN is to use lidar remote sensing for the extraction of the object heights such as tree heights or generally the height of the vegetation. The height is an important variable in the different types of monitoring and inventory systems. It is a basic parameter for planning. A further aim is to extract other variables which can be derived from the lidar data. Another field of the project deals with the protection of high voltage power supply lines. The conclusion in this research field is drawn depending on the information which are extracted from the lidar data, too. For example power supply lines have to have a minimum distance to different objects such as trees, people, cars, buildings, etc. Therefor the lines have to be checked periodically to detect the changes in the area of the supply lines. If varying objects like trees reach a special height so that the distance from their top to the lowest line is too short, the trees have to be cut. In the past this information was collected manually.

In Germany forest inventories are derived every ten years. The forest inventory generally consists of three parts. The first one is involved with the determination of the current state, that means the estimation of tree species and tree species distribution, timber volume, stand inventory, increment, etc. The second one is the supervision of the execution of the planning for the last decade. The last one provides the planning for the following decade. In the following forest inventory means in this article the first part of the three steps. This inventory is an expensive system due to the fact that the information of the current state in particular is measured manually. Furthermore only aerial photos are used to delineate the forest stand units. In a further step the analogue datasets have to be digitalised. Variables like mean tree height, tree species distribution, cover densities, etc. are estimated by field surveys and calculated for each stand unit using statistical methods.

During the last years the interest has grown to decrease the costs of these inventories by reducing the time effort. For these different kinds of inventory systems lidar remote sensing offers great possibilities. Many studies have shown this suitability before. But still there is a lack of applications. In the project NATSCAN are several approaches for the automatic extraction of the needed information researched. Within the project an enhanced demonstrator lidar sensor will be developed by TopoSys and tested at Felis. The main advantage of the new system will be a higher spatial resolution and homogenous foot print distribution.

2. MATERIALS

2.1 Study areas

There have been chosen three study areas for the development of the algorithms in the project. The study areas should combine as many different characteristics of forest stands as possible. The first area is in the Northwest of the city Freiburg/ Breisgau. It is planar at a height of about 250m above sea level. The tree species distribution and age class distribution is diversified. Furthermore the tree species occur in mixed stands. In contrast to this the second study area is in the Southeast of Freiburg. It is a mountainous area with a height from 500 to 900m above sea level. There occurs the typical mountain mixed forest. The tree species distribution is diversified, too. The third area has been chosen for the extraction of man made objects and the development of algorithms for the inventory system used at power supply lines. It is near by the city Engen/ Lake Constance and it is mostly planar or slightly mountainous.

2.2 Data sets

In the project different types of data sets are used – laser-, multi-spectral- and GIS-data. The data sets are collected and used as described in the following.

2.2.1 LASER AND MULTI-SPECTRAL DATA

The lidar and multi-spectral data used are recorded during spring and summer 2002 by TopoSys with their FALCON system. The used laser scanner device is a discrete return lidar system. It records the first and the last pulse of each laser beam simultaneously. The lidar sensor consists of 127 fan-formed glass fibre cells at the input and at the output side. Another cell is used for the calibration. The angle between the cells amounts 2mrad. The laser light is sent off with an angle of 1mrad. This means, that the footprint has a diameter of 1m at a flight height of 1000m. The sensor device consists not only of the laser scanner, but contains a digital line scanner. It is able to record RGB and NIR data. Each scan line has 682 pixel at a resolution of 0,55m at 1000m survey height. The wave length of the channels are 440 – 490nm in channel 1, 500 – 580nm in channel 2, 580 – 660nm in channel 3 and 770 – 890nm in channel 4.

2.2.3 FOGIS

The abbreviation FOGIS means “Forestal Geographic Information System Baden-Wuerttemberg”. FOGIS is the digital result of the forest inventory of the government of Baden-Wuerttemberg. For each forestry office this inventory is done every decade. The results of the field surveys are drawn in maps, which are digitised with a special FOGIS-software based on ArcInfo©. The GIS-geometries are relayed to a special data base, which contains the information about tree species, tree age, tree height, stem diameter, standing volume, etc. The forest inventory is the execution control of the last ten years and declares the planning for the following decade.

3. METHODS

3.1 Single tree delineation

The extraction of single trees in very dense forest areas is compared to the estimation of man-made objects an even more difficult task as nature is chaotic: no right angles, no plan surfaces, no distinct delimitation between objects exist. The delineation of single trees or groups of trees is done in a sequential manner.

So far the procedures developed are based on the rasterised digital surface model (**DSM**) and the digital terrain model (**DTM**). For the development the HALCON image processing software has been used. It is a developing system mainly used in the area of machine vision applications and consists of a huge library of image processing routines, which can be integrated into own software developments based on C, C++ or COM. Additionally it provides the developer with a case tool called Hdevelop.

3.1.1 NORMALIZED DIGITAL SURFACE MODEL [nDSM] AND THE SMOOTHING MODEL [SNDSM]

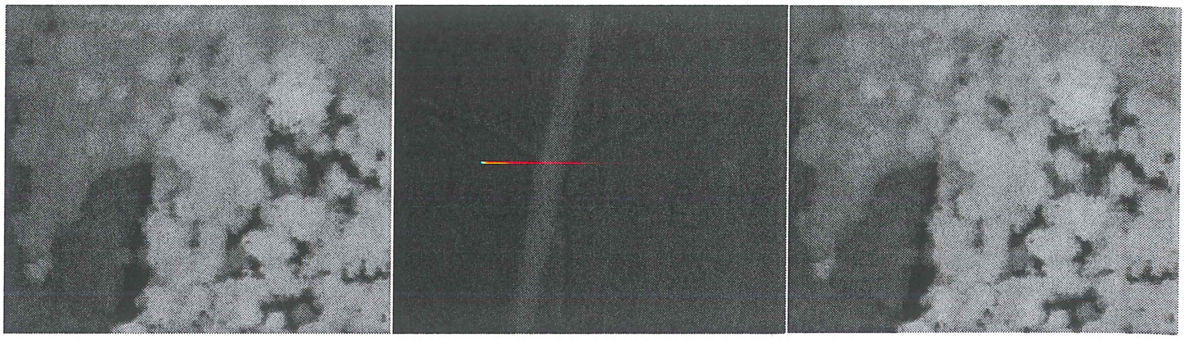
The first step in the processing chain is the calculation of the normalised digital surface model (nDSM) by subtracting the DTM from the DSM. This step should only be used in areas where no extreme topography occurs, otherwise the surface, which in fact represents the canopy of the trees, is changed and the tree delineation will produce falsified results.

Thereafter the forest area is classified into "old growth" and "young growth" regions. As threshold conduced the tree height. Trees which are higher than 22m, especially broad-leafed trees, have quite large height variations in their crown topography. The variations can in a later step be used to distinguish between broad-leafed and coniferous trees. In this basic state, where the interest is concentrated on the delineation of single trees or groups of trees, these variations worsen the desired results of the delineation processes.

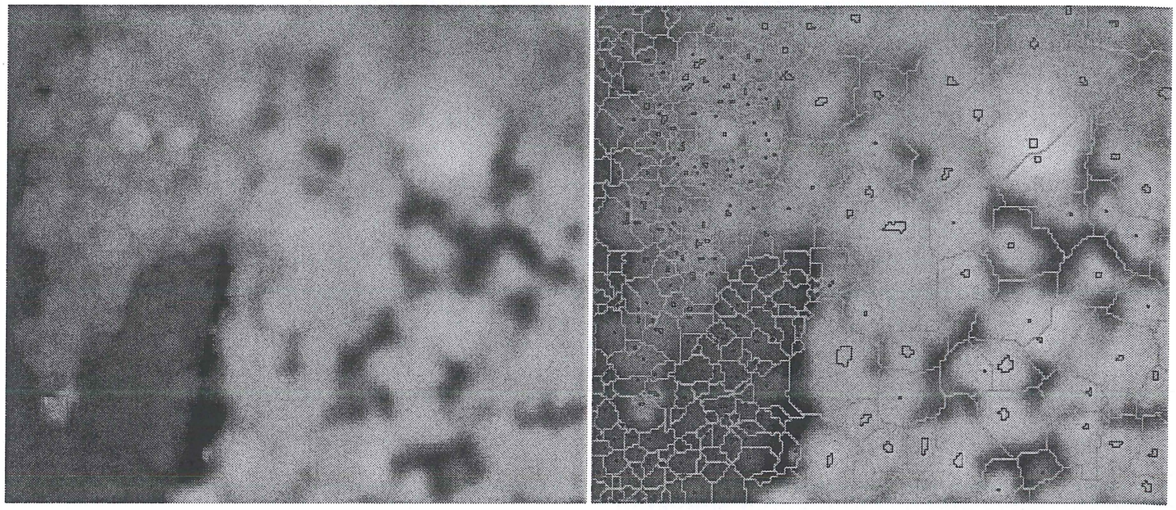
Figures 1a,b show the DSM and DTM and figure 1c the calculated nDSM. The nDSM has been grouped into two domains "young growth" and "old growth". The "old growth" domain has been filtered by a Gaussian filter with a large sigma to smooth the rough tree canopies to avoid an "over-segmentation" by the following pouring algorithm. In the "young growth" domain none or only a very "mild smoothing" has been done, otherwise tree crowns would be spuriously merged. After the filtering processes the domains have been merged to the smoothed nDSM (**snDSM**), see figure 2a.

3.1.2 POURING – THE RAINDROP MODEL

A pouring algorithm is used to estimate both tree tops and corresponding "light crown boundaries" in the snDSM. The pouring algorithm is provided by the HALCON software and works similar to a watershed algorithm. It assumes the input data describing a "mountain range". Firstly the local maxima are calculated. Gray-values, i.e. tree heights, which have larger values than their 4-connective neighbours are marked as maxima. Secondly, starting from these maxima an expansion is done until the valley-bottoms are reached, like raindrops running downhill in all possible directions. This part of the algorithm continues as long as the examined points found are smaller or equal. Thereby some points of the valley-bottom can belong to several maxima. In a final step these unsure points are assigned by a uniform expansion of all affected regions, see figure 2b.



*Figures 1: 1a) shows the **DSM** from the test site West of Freiburg (South Germany); 1b) shows the **DTM** and 1c) shows the normalised DSM (**nDSM**), calculated by subtracting the DTM from the DSM. Tree heights can by measured directly in this model.*



*Figures 2: 2a) **snDSM** – Areas with tree heights less than 22m are classified as "young growth" and where the heights are greater than 22m are "old growth". The **nDSM** has been smoothed by Gaussian filter with different sigma, depending whether it is "old growth" or young growth". 2b) Result of the **Pouring** algorithm. The green border lines show the created tree regions and the small blue ones the pouring maxima regions. The algorithm does not stop at the tree border, but at the bottom-valleys, which e.g. can be the real surface or small trees with a more or less flat crown standing between two or more large trees.*

3.1.3 Form Parameters and Mutual Relations

There still exists a lot of mismatched, merged or not recognised trees, e.g. a substantial amount of regions which are too small or have shapes which are impossible for being trees.

To enhance the result the following parameters and relations have been introduced:

Removal of border trees: Trees lying at the image border are dissected and falsify the calculation. Therefore they are extracted and suppressed.

Minimal area: All regions consisting of equal or less than an choosable "area threshold", depending on the tree height are assumed not to be separate trees, but part of an adjacent tree. These regions are merged with that neighbouring tree having the longest "border line" in common.

Anisometry (Ratio of radius r_a and r_b): The parameter anisometry describes the ratio of two estimated radii lying perpendicular to each other in the two main directions of the region. For a circle this value is 1.0. If this ratio is too large, which means that the region has a very long but narrow shape, it is improbable that this region represents a tree. If there is no plateau in the region it is merged to the adjacent region with the most similar orientation. Plateaus are calculated in the unfiltered 16bit image (DSM) as the highest points in the 4-connectivity or 8-connectivity neighbourhood. Otherwise no merging takes place

Compactness: The compactness of the extracted tree regions is examined. It is defined as the ratio between the squared circumference and 4*pi*area. A circle has a compactness of 1.0. The value becomes smaller in case that the corresponding shape differs more and more from a circle. It is assumed that a tree crown has more or less the shape of a circle or ellipse. Depending on the shape of single tree the delineation is improved either by opening or closing, two morphological operators. Overlapping regions are separated.

Minimal distance between tree tops (pouring maxima): Finally, the distance between tree tops of neighbouring regions is examined. In case that the distance is less than "distance threshold" again depending on the tree height the two adjacent regions are merged. The result of this process is shown in figure 3.

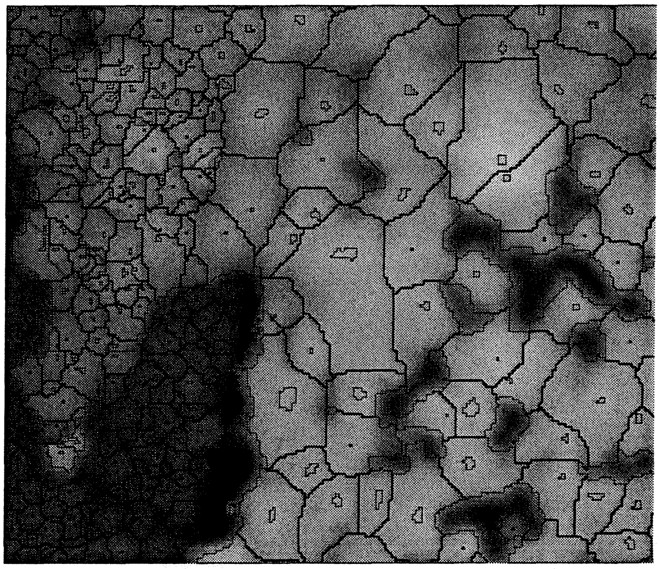


Figure 3: ***Merging Algorithm*** *- The regions calculated by the pouring algorithm are changed. The blue border lines show the corrected and the red ones the part of the border lines, which have been originally calculated by the pouring algorithm.*

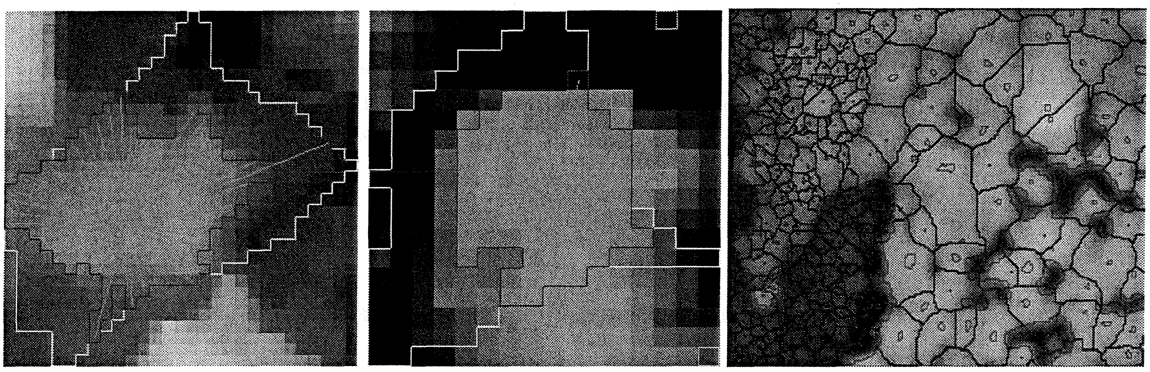


Figure 4: ***Ray-algorithm*** *- 4a,b) show two examples, where the regions created by the pouring algorithm are reduced, based on a slope criteria. 4c) shows the final result after the ray algorithm. The blue border lines show the new corrected and the red ones the part of the border lines, which have been calculated by the merging algorithm.*

3.1.4 Ray-algorithm

The enhanced tree area can still contain parts of the real surface or include small trees which have a more or less flat crown and stand between the large trees. This is caused by the fact, that the pouring algorithm executes until all bottom lines in the whole image are found. Therefore the border lines do not always represent the border of the trees. This means that several tree crowns are estimated too large. Therefore the "ray-search algorithm" is included and it works as following:

- Choosing approximate tree tops. It is assumed, that the maxima extracted by the pouring algorithm represent the tops of the trees. These points are the starting positions of the algorithm.

- Calculation of rays between the maxima and a special amount of border points.
- Along each ray the difference in elevation is calculated within distinct arbitrary chooseable steps. A difference in elevation of –2.0m/0.5m was empirically chosen as threshold, but can be adapted based on the tree height.
- If the calculated elevation is negative and smaller than the threshold, the position on the ray is marked as a new border point. Otherwise the original border point, which is the end point of the examined ray, will be retained.
- Creation of the new tree crown by calculating the new border polygon based on retained border points and the new ones.

The ray-search algorithm is proceeded for all tree regions. Two test regions and the final result is shown in figure 4.

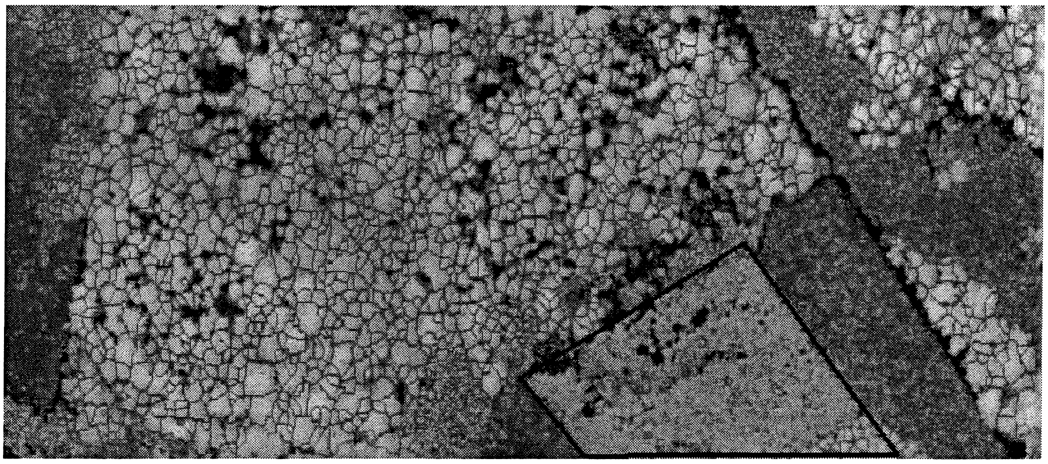


Figure 5: The classification of the two main forest groups broad-leafed trees and conifers is based on the ratio between "light crown height" to "light crown area". The green bordered regions are classified as conifers and the red ones as broad-leafed trees. The blue bordered region is a conifer area extracted from FOGIS.

3.2 Classification of broad-leafed trees and conifers by the ratio "light crown height " versus "light crown area"

Up to now just one criterion for the classification of the two main groups of trees – broad-leafed trees and conifers has been investigated. It is the ratio "light crown height" to "light crown area". The ratio becomes larger for conifers than for broad-leafed trees. Unfortunately this is not true for young broad-leafed trees as they almost have the same shape as conifers. Therefore the ratio should only be used in areas, where young broad-leafed trees do not occur. As the aim is to distinguish between the two groups, all areas with young trees should be excluded from the investigation concerning this criterion. The final result of all processing steps concerning tree delineation based only on laser data is presented in figure 5.

3.3 Estimation of stand characteristics

3.3.1 STAND UNIT DELINEATION

As mentioned above first of all a nDSM has been calculated. After that every pixel value expresses the object height and here the tree height respectively. The image is filtered in different ways for the extraction of the different stand units. This is done under the assumption, that stand units could be differentiated by their height characteristics. The different closeness of the canopy should lead to characteristical criteria, which can be used for the segmentation. Every segmented region is cut out to avoid multiple segmentations. Without that it would lead to errors or interferences. Every following segmentation step is operated at the newly reduced image. The easiest step is using the original tree height with a segmentation at a threshold at 15m. This is possible due to the fact that young forest stands have a homogenous canopy, which is mostly closed. This is the only step using a real tree height. All other segmentations are calculated after the use of a special filter. Every filter emphasises the according criteria of the extracted stand unit. For one step a mean smoothing filter is used which is able to smooth in a defined range of gray values. The filter mask has a size of 15 x 15 pixels. This is useful to extract stand units that are dominated from broad-leafed trees with a height above 25m. Another filter calculates the local deviation. This is very capable to detect stand units with a homogenous texture like young planted coniferous trees. The uniformly character of this stand type can be easily used for the segmentation. After the extraction of a stand unit, the delineated area is cut of the original image. Thus once detected the stand unit doesn't influence the following segmentation steps. The figure 6 shows the result of the automatic delineation of the stand units. With the used algorithm it is possible to divide the image in the different stand units.

3.3.2 MEAN STAND HEIGHT

Depending on the single tree delineation a mean stand height for each stand unit is calculated. The automatic delineated crown shapes represent the dominant trees in each stand unit. Their heights are used to calculate a mean stand height of the dominant species. The single tree shapes are extracted as described above. For every tree crown shape the maximum gray value is recorded assuming that this value is the top of the tree. Furthermore the position of every maximum value is extracted, too. Thus an index of every stand unit is assigned to every maximum height value, which belongs to the corresponding stand unit. Using this index it is possible to calculate the mean height for every stand unit. Furthermore the values can be visualised by their position to verify, whether they really represent the tree tops or not.

3.3.3 CROWN DENSITY

The calculation of the crown density in each stand unit depends on the single tree delineation, too. First the area of every stand unit and second the area of every crown shape is calculated. Thereafter the shapes of the crowns and the stand units are clipped. The crown covered area is set in ratio to the area of the corresponding stand unit. The result is the crown density in each stand unit. With this parameter it is possible to draw conclusions to the stand density.

3.4 Comparison between GIS and automatic delineation

The FOGIS delineation is provided using ortho aerial images. It is done by visual interpretation and is proofed by field surveys. However figure 7 shows that the FOGIS data contains errors. The courses for these errors are on the one hand errors done by the interpreter and on the other hand errors during the digitalisation. The arrows mark two points, where the line management is not comprehensible. Furthermore figure 7 shows one important aspect. The automatic delineation could be done well only depending on the height information of forest stands. It is possible to use the screened lidar data to extract stand unit boundaries automatically. Indeed it has to be said, that the automatic line management is not as straight as the one of a human interpreter. This is caused by the fact that the automatic delineation depends on the boundaries of the tree crowns. This means that the older the trees in the stand unit are the more frayed is the line management. This is increased the greater the used filter mask is.

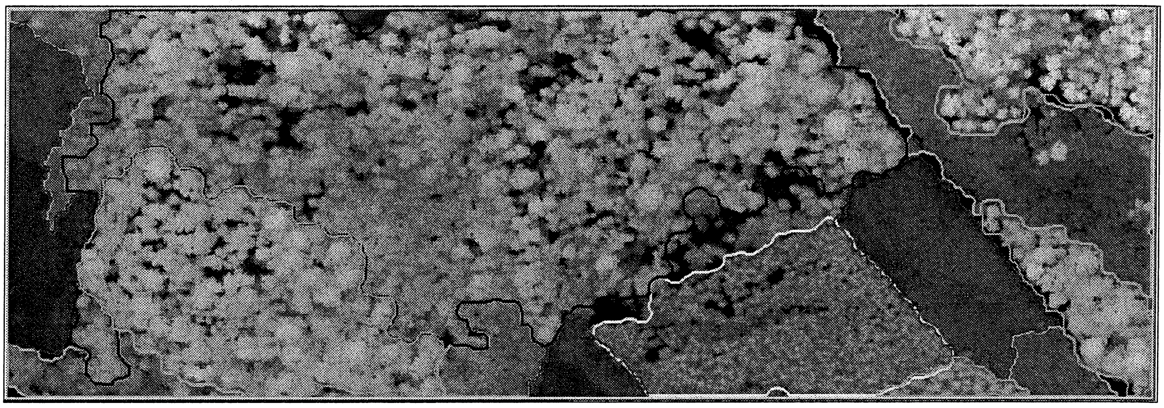


Figure 6: Result of the stand unit delineation.

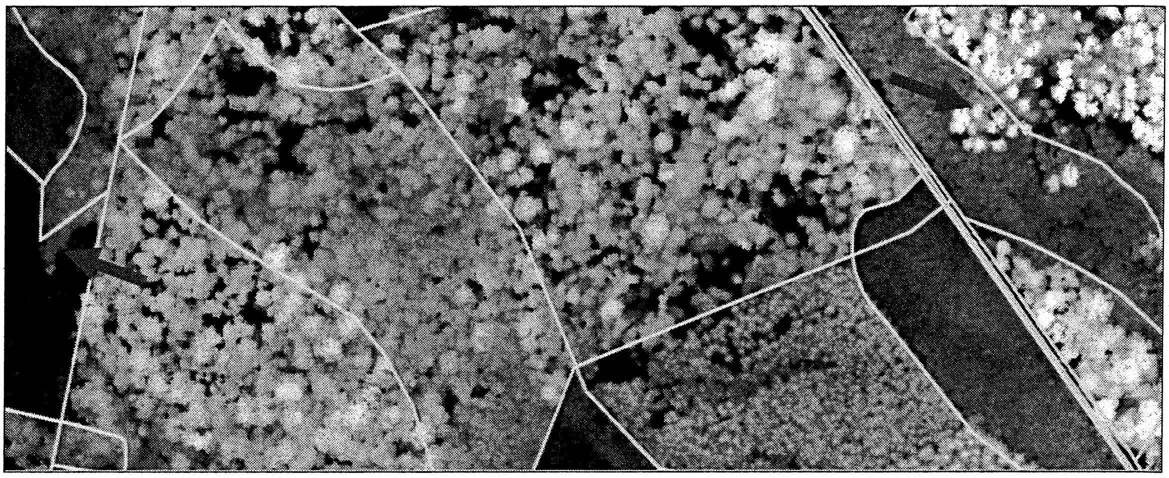


Figure 7: FOGIS Delineation. The red arrows mark two examples for errors in the line management. In comparison to figure 6, it becomes apparent that the algorithm for the automatic stand unit extraction works well. (FOGIS data from the government of Baden-Wuerttemberg).

4. DISCUSSIONS

A hundred percent correct solution will never be reachable in our opinion, especially with an automatic inventory method. In several cases this is not possible either for an interpreter to determine from top view, whether a scanned object describes a single tree or a part of a tree crown. It is obvious that in such a case a computer detect anything more. The most significant problem occurs at the extraction of the single tree crowns. Especially in forest stands that consists mainly of older broad-leafed trees it is difficult to detect the right crown shape. Very often one great tree crown is divided in three or four big branches. Every branch is detected as a single crown and sometimes it is not possible for a human to identify the right crown shape. However, compared to the methods used for forest inventory, the laser-based methods will satisfy the requirements both in a faster and more economic way, if it is possible that the estimated results are reliable within a defined limit. For forest inventories often the old yield tables are used. Many studies have shown, that these tables are uncertain to estimate the timber volume. The results of the laser scanner data deviate from the forest inventory inevitably. Therefore a special field survey has been implemented. But the parameters of this survey still have to be calculated so that so far no exact reference exists.

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ESTIMATION OF ABOVEGROUND BIOMASS FROM AIRBORNE LASER SCANNER DATA WITH CANOPY-BASED QUANTILE ESTIMATORS

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ABSTRACT

In this study, airborne laser scanner data were used to estimate total aboveground biomass for tolerant hardwood forests composed predominantly of mature sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britton) in the Turkey Lakes Watershed (47° 03' N 84° 25' W) near Sault Ste. Marie, Ontario, Canada. Ground reference data were collected during the first two weeks of July, 2000 for 44 circular sample plots, each 0.04 ha (or 400 m^2) in area. ALS data were acquired on August 24, 2000 using an Optech Airborne Laser Terrain Mapper (ALTM; model 1225). It is assumed that the vertical distribution of lidar is related to the vertical distribution of foliage/needle area following a simple quantile-quantile relationship. Based on this assumption, so long as a consistent canopy-based quantile estimator is selected, aboveground biomass should be able to be estimated. Five models, each based on different, yet consistent canopy-based quantile estimators, are tested. All five models were comparable with coefficient of determination values ranging from 0.76-0.82 and RMSE ranging from 1.59-1.80 Mg/ha.

INTRODUCTION

For the purpose of updating forest inventories or expanding forest inventories to include areas for which little or no information has been previously available, light detection and ranging (lidar) may become the choice remote sensing platform for these sampling and mapping tasks. The key advantage of lidar that distinguishes it from other remote sensing technologies (i.e., optical and radar) lies in its capability to readily provide measures of tree/canopy heights. A rich body of literature exists in the forestry and forest science domains where several allometric relationships for trees have been explored. The classic example would be the commonly used relationship between diameter-at-breast height (DBH), measured at 1.3 m aboveground level, and total and component tree biomass (Ter-Mikaelian and Korzukhin, 1997). Surrogate variables for DBH have also been explored, such as crown size (Wile, 1964), and crown width in combination with tree height (Bonnor, 1964). The ability to measure DBH or surrogate variables for DBH from remotely sensed data would allow existing allometric relationships to be exploited. The opportunity also exists for lidar remote sensing for forest research to develop new remote sensing-based estimators.

The purpose of this paper is to present a theory on the relationship between the vertical distribution of laser returns and foliage/needle area, and how canopy-based quantile estimators could be used as an estimator of aboveground biomass. Although this paper only reports results for the estimation of aboveground biomass, our approach should be equally applicable to other biophysical properties according to theories from the biological scaling literature (Niklas, 1994).

LIDAR AND FOLIAGE/NEEDLE RELATIONSHIP

Magnussen and Boudewyn (1998) demonstrated for Douglas-fir that the vertical distribution of laser returns was related to the vertical distribution of needle area according to a simple quantile-quantile relationship. In other words, if 25% of the lidar returns were found above a canopy height x, 25% of the needle area could also be expected to be above that level. We assume with lidar remote sensing that this relationship holds for other species. In turn, foliage/needle mass can be derived from foliage/needle area providing that specific leaf area (SLA) for the tree species is known. If we were to assume that SLA did not change downwards through the canopy, we can expect lidar to be capable of estimating foliage/needle biomass. According to some theories from biology, such as the pipe-model theory, various characteristics of a tree, such as needle/foliage and total mass, are constrained by the basal diameter of the tree (i.e., DBH). Consequently, a relationship between needle/foliage and total mass exists. This relationship can be exploited to estimate total aboveground biomass with lidar-based remotely sensed estimators. So long as a consistent canopy-based quantile estimator is selected across sample plots, a consistent proportion of foliage/needle area and mass are measured and thus, total aboveground biomass can be estimated based on known allometries. The results from using five linear models to estimate total aboveground biomass, each based on different but consistent canopy-based quantile estimators, are presented.

STUDY AREA

The study area was the Turkey Lakes Watershed (TLW) (47° 03' N 84° 25' W) located approximately 60 km north of Sault Ste. Marie, Ontario, Canada (Figure 1) near the northern edge of the Great Lakes-St. Lawrence forest region on the Canadian Shield. The old-growth hardwood forests found in the TLW are predominantly composed of uneven aged mature to overmature sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britton). A sustainable forest harvesting project was implemented in the TLW in 1997 to explore the impacts of various silvicultural treatments on the forest ecosystem (Morrison *et al*., 1999). Four treatments were applied to a total of 17 harvest blocks including: (i) clearcut; (ii) selection; (iii) shelterwood; and (iv) control (i.e., no treatment).

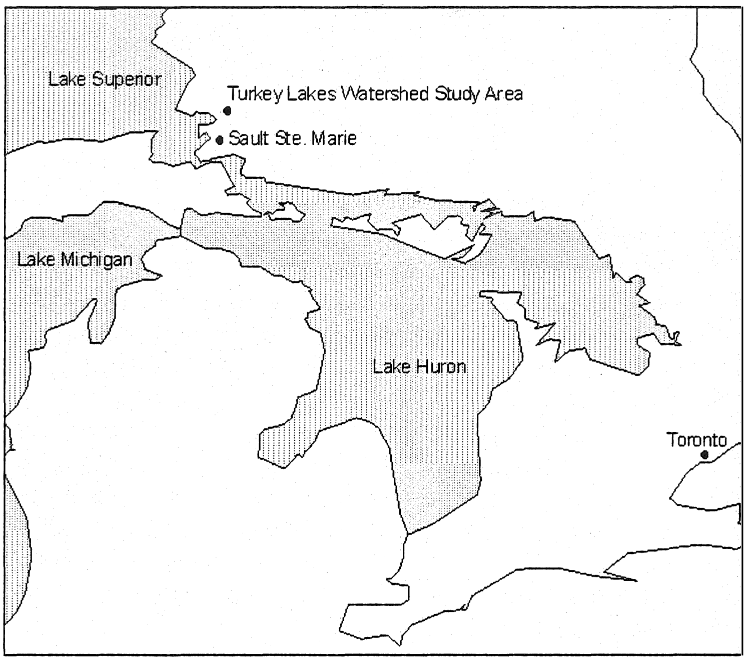

Figure 1: The geographic location of the Turkey Lakes Watershed study area in Canada.

GROUND REFERENCE DATA

Ground reference data were collected during the first two weeks of July, 2000. Thirty-six circular sample plots, each 0.04 hectare (ha) (or 400 m^2) in area, were randomly distributed across the harvest blocks. Another eight sample plots were established just slightly beyond the boundary of the harvest blocks in undisturbed forests and can be considered as additional control treatment plots. The location and type of each sample plot are presented in Figure 2. In addition to recording the species of trees with a DBH greater than 9 cm, DBH and tree height were measured on each plot using a diameter tape and vertex hypsometer, respectively. A threshold DBH of 9 cm was selected as per Canada's National Forest Inventory sampling protocol for 0.04 ha plots (Gillis, 2001). Site-specific biomass equations (Morrison, 2002) were used to derive estimates of total aboveground biomass for the sample plots. Summary statistics for the sample plots are summarized in Table 1.

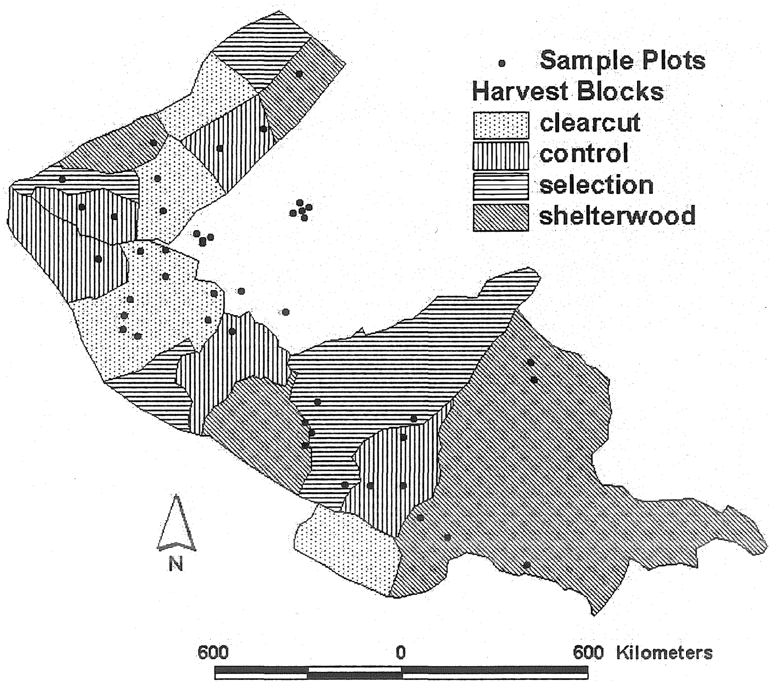

Figure 2: The spatial distribution of the 44 sample plots over the TLW harvest blocks.

Table 1: Summary statistics of 44 sample plots in the harvest blocks of the TLW.

Variable	*Mean*	*Median*	*Minimum*	*Maximum*
Diameter (cm; 1.3 m aboveground)	22.7	18.6	9	81.6
Maximum height (m)	17.8	17.5	7.6	32.6
Biomass (Mg/ha)	138.3	138.8	2.2	306.0

LIDAR DATA

The TLW was surveyed on August 24, 2000 using an Optech ALTM 1225 with the survey parameters described in Table 2. The harvest block areas in the TLW were surveyed by two sets of flight lines in different direction for the purpose of increasing the laser point density. Classification of the lidar three-dimensional point cloud into ground and vegetation returns was carried out by a lidar service provider. Over 50 million lidar returns were acquired over the 1000 ha TLW.

Table 2: Lidar system configuration for survey of the TLW using an Optech ALTM 1225.

Parameter	*Value*
Pulse rate	25 kHz
Scanning frequency	15 Hz
Scan range	± 15°
Collection mode	First and last return, and intensity
Laser wavelength	1047 nm
Aircraft platform	Piper Navajo
Aircraft altitude	750 m
Aircraft velocity	60 m/s
Swath	400 m
Lateral post spacing	0.6 m
Forward post spacing	2.0 m
Footprint size	20 cm
Overlap between flight lines	25%

METHODS

Ground DEM from Laser Data

In order to derive canopy heights, a ground reference level is required, which is derived by interpolating a digital elevation model (DEM) using those laser returns that have been classified as ground. A DEM for the TLW with a cell resolution of 1.0 m was derived using the inverse distance weighted interpolator. Given the large number of *x,y,z* points characteristic of lidar data, any other spatial interpolator would have also been a suitable interpolator (see Lloyd and Atkinson, 2002). A comparison of the DEM values with validation data collected along two transects in the field using traditional surveying techniques (n = 47) resulted in an root-mean-square error (RMSE) of 0.27 m.

Laser Canopy Heights

For each vegetation laser return's *z*-value, by subtracting the DEM *z*-value corresponding to its *x-y* coordinates yields laser vegetation heights. However, Figure 3, a graph where the laser vegetation heights are plotted against their matching DEM heights for a randomly selected sample plot, clearly shows that some laser returns are misclassified as vegetation and that the vegetation class consists of understory and canopy laser returns.

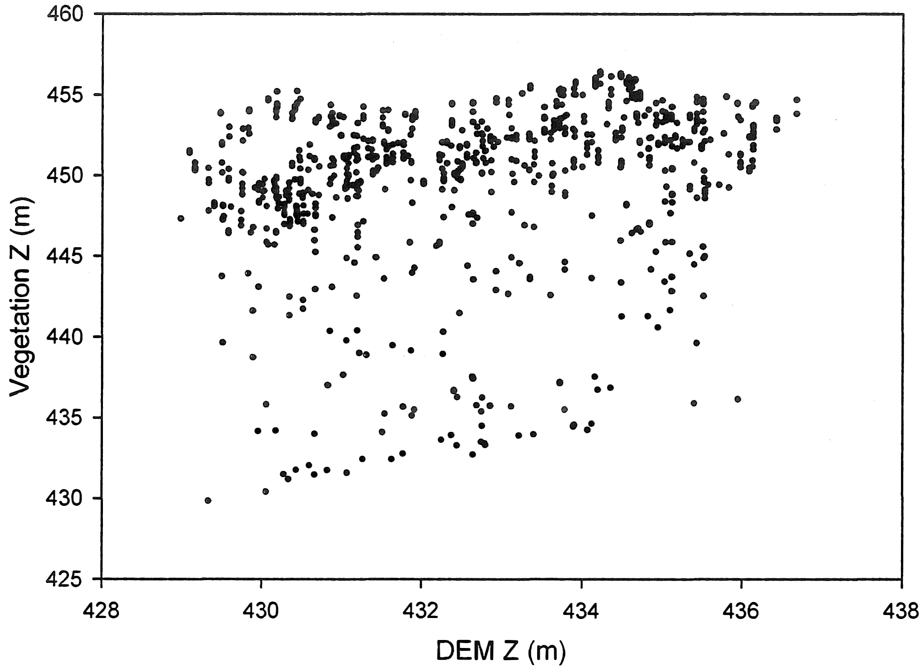

Figure 3: Z-values of vegetation returns plotted against their corresponding DEM z-value with matching x-y coordinates.

As we are assuming that the vertical distribution of laser returns is related to the vertical distribution of foliage area within the canopy, it is necessary to separate the vegetation returns into a canopy class and an understory class (i.e.., non-canopy returns). We adopt an approach similar to the one taken by Magnussen and Boudewyn (1998), where a segmentation algorithm using expectation-maximization (EM) (Dempster *et al.*, 1977) was used to statistically separate the laser canopy return from the other classes, thereby avoiding the use of a 'hard' threshold (e.g., filter all laser returns less than 5 m).

The premise of the EM algorithm used here is to initialize two linear models with random parameter values and then iterate until the parameter values converge. The iteration process consists of two steps: an expectation (E) step and a maximization (M) step. During the E-step, for each data point, two weights are calculated, with both weights summing to 1. The weights are calculated using a 'softmin' function (Eq. 1 and 2) that uses as input the residuals from two linear models with known parameters (Eq. 3 and 4). The model parameters are calculated during the M-step using weighted least squares (Eq. 5). Data points are assigned to the model with the minimal residual value. The

E- and M-step are iterated until model parameters converge. The results of applying a segmentation algorithm using EM to a randomly selected sample plot are shown in Figure 4. On average ten iterations were required for the parameter values to converge. For each sample plot, laser canopy returns were classified using the above described algorithm.

$$w_1(i) = \frac{e^{-r_1^2(i)/\sigma^2}}{e^{-r_1^2(i)/\sigma^2} + e^{-r_2^2(i)/\sigma^2}} \quad \text{Eq. 1}$$

$$w_2(i) = \frac{e^{-r_2^2(i)/\sigma^2}}{e^{-r_1^2(i)/\sigma^2} + e^{-r_2^2(i)/\sigma^2}} \quad \text{Eq. 2}$$

$$r_1(i) = a_1 x_i + b_1 - y_i \quad \text{Eq. 3}$$

$$r_2(i) = a_2 x_i + b_2 - y_i \quad \text{Eq. 4}$$

$$\begin{pmatrix} \sum_i w_i x_i^2 & \sum_i w_i x_i \\ \sum_i w_i x_i & \sum_i w_i 1 \end{pmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \sum_i w_i x_i y_i \\ \sum_i w_i y_i \end{bmatrix} \quad \text{Eq. 5}$$

Statistical Analysis

A multiplicative model formulated as Eq. 6 was selected, which can be translated into linear form according to Eq. 7. This type of model has been used successfully by others to model various forest biophysical properties (e.g., Mean *et al.*, 1999; Næsset, 2002; Lim *et al.*, in press). The log transformations required in Eq. 7 also ensures in most cases that regression assumptions are not invalidated. Total aboveground biomass is used as the dependent variable, whereas the laser height metrics corresponding to given canopy-based quantiles (i.e., 0^{th}, 25^{th}, 50^{th}, 75^{th}, and 100^{th} percentiles) are utilized as independent variable. Natural log transformations are applied to the dependent and independent variables. Consequently, a total of five linear models were derived.

$$g = \beta_0 {h_L}^{\beta_1} \quad \text{Eq. 6}$$

$$\ln g = \ln \beta_0 + \beta_1 \ln h_L \quad \text{Eq. 7}$$

where g is the forest metric of interest, h_L is some laser height corresponding to a given canopy-based quantile, and β_0 and β_1 are regression coefficients.

RESULTS

The least-squares fit for the five models are depicted graphically in Figure 5. For the models using the 50^{th} and 75^{th} percentile, one plot, which corresponds to a clearcut plot, falls out and no longer fits the general linear relation. Further examination of the ground reference data for the clearcut plot reveals that the sample plot consists of only a single tree. Because of the presence of a single tree, the majority of laser returns likely penetrated through the tree canopy resulting in the 50^{th} percentile and beyond not corresponding to measures of the tree canopy, but instead near ground returns. Consequently, the single clearcut plot was removed from the regression for the 50^{th} and 75^{th} percentile models (new least-squares fits in red in Figure 7). The same holds for the 100^{th} percentile model, where the 100^{th} percentile for the clearcut sample plot is, in fact a negative canopy height. The negative tree height was derived as a result of the overestimation of the ground in the sample plot and when the natural log of a negative value is taken, an exception to the calculation is created. Therefore, the clearcut plot was not considered in the 100^{th} percentile model.

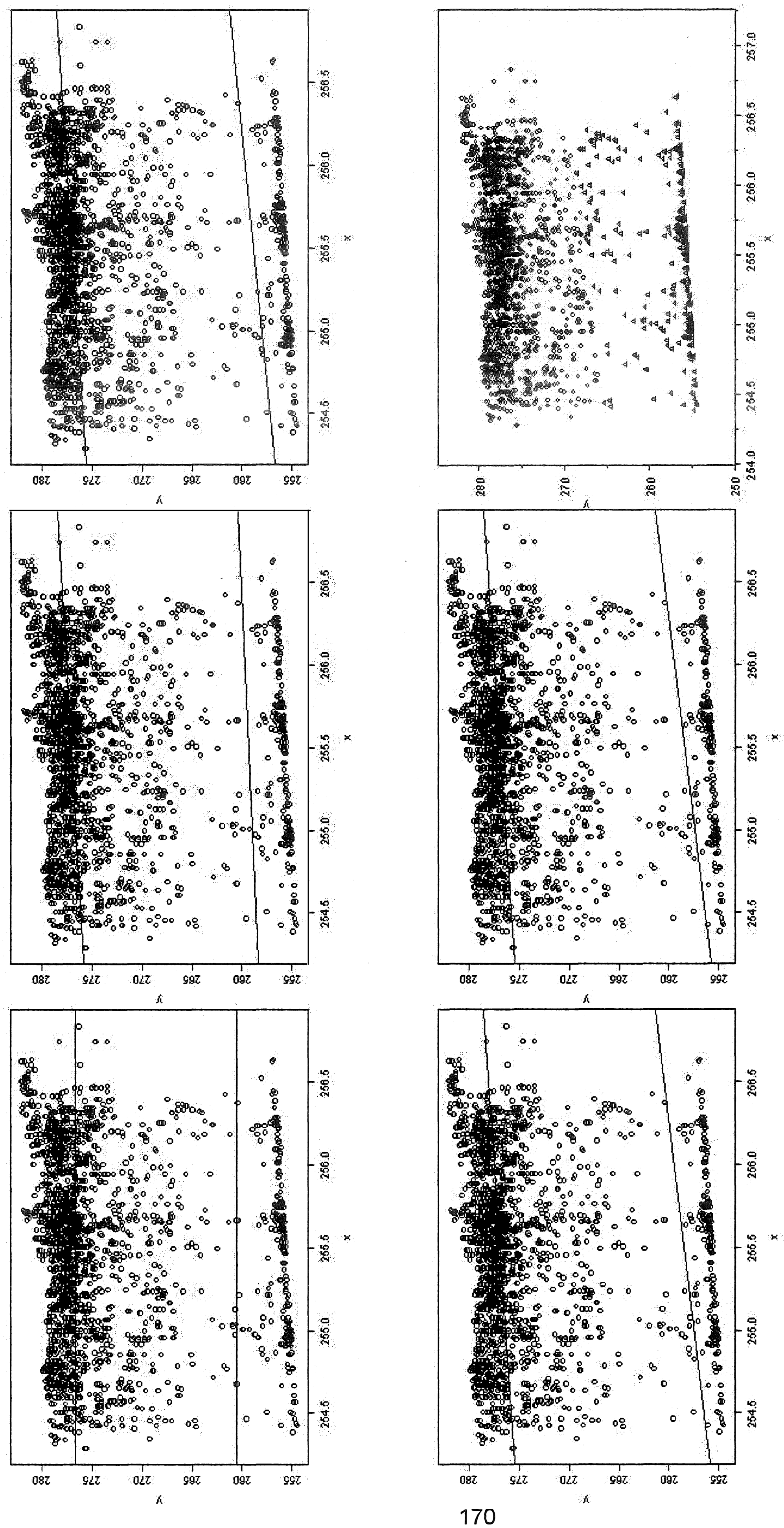

Figure 4: An example of the iterations from the segmentation algorithm using EM for a randomly selected sample plot. Laser canopy and non-laser canopy returns are depicted as circles and triangles, respectively, in the final graph in the bottom left (colour figure).

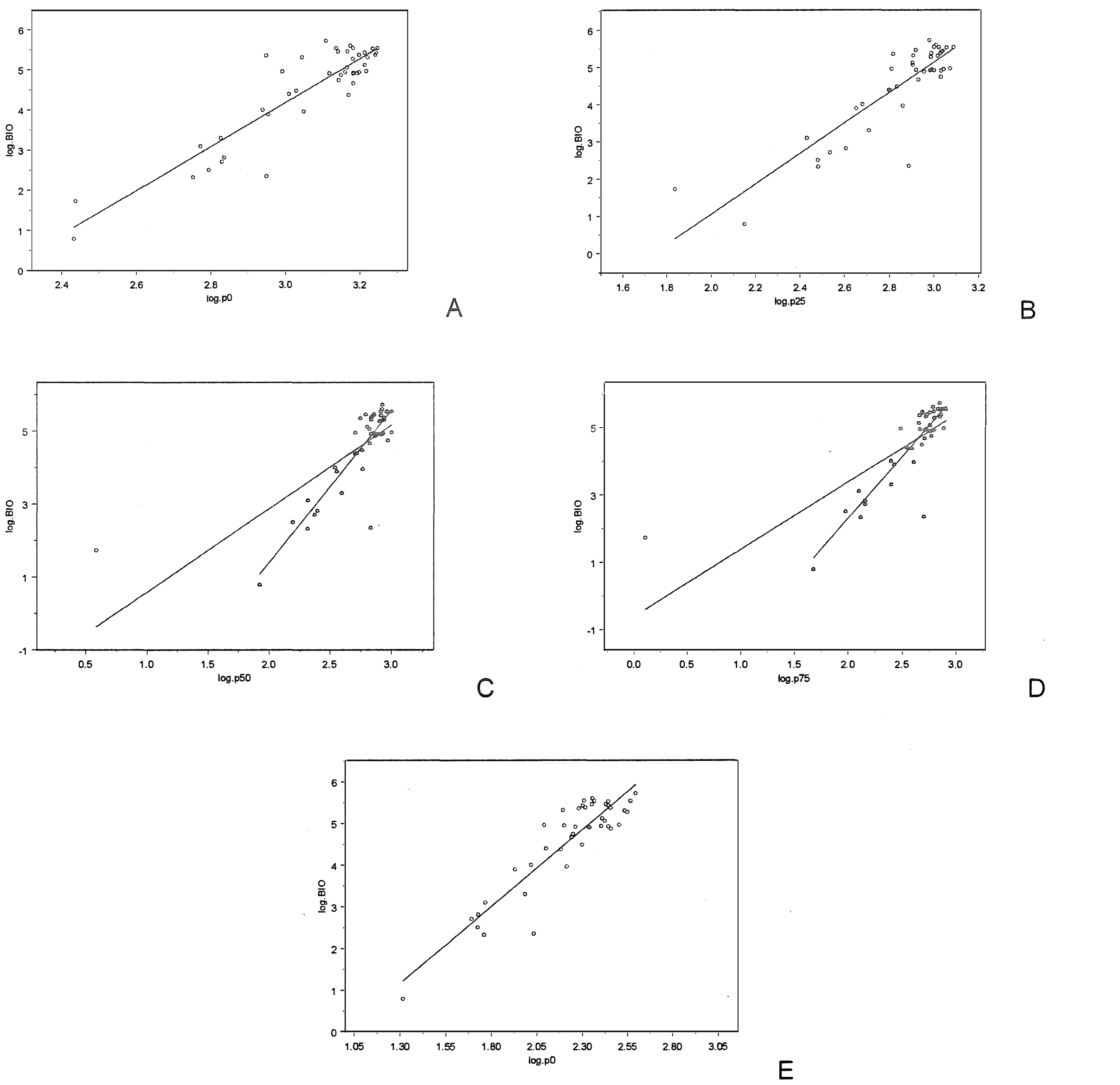

Figure 5: Least-squares fit for the 0th percentile (A), quartile (B), median (C), 3rd quartile (D), and 100th percentile (E) models (colour figure).

The coefficient of determination (r^2) and RMSE values for the five models tested are summarized in Table 3. The r^2 values for the five models are all very similar as is the case for the RMSE.

Table 3: Statistical results of the five linear models tested using canopy-based quantile estimators.

q(LHT)	*p-value*	r^2	*RMSE (Mg/ha)*	*n*
0.00	<0.001	0.816	1.67	44
0.25	<0.001	0.756	1.80	44
0.50	<0.001	0.772	1.71	43*
0.75	<0.001	0.791	1.67	43*
1.00	<0.001	0.820	1.59	43*

* A clearcut sample plot was excluded from the regression.

CONCLUSIONS

Although the five models were not tested to determine if they were statistically different from one another, the results provide preliminary support for the concept of canopy-based quantile estimators for aboveground biomass. A key assumption made was that the vertical distribution of lidar returns was related to the vertical distribution of foliage/needles for tree species; however, the assumed quantile-quantile relationship requires further validation. In addition, the TLW forest is a relatively homogeneous forest and how canopy-based quantile estimators for aboveground biomass perform in more heterogeneous and structurally complex forests remains untested.

At present, the same approach presented in this paper is being tested with ground reference and lidar data from Shawnigan Lake, which was the data used by Magnussen and Boudewyn (1998). The relationship between needle area and lidar was reported on and therefore the assumption made in this research with sugar maple is not required with that data. The capability of other laser height metrics for estimation of biophysical parameters are also being explored (Lim *et al.*, in press).

Many lidar-related studies have been published demonstrating the capability of the technology to estimate forest properties of interest to forestry and beyond (reviewed by Lim *et al.*, 2003). However, attention also needs to be placed on addressing the question of why various laser height metrics themselves are successful estimators. Answers to this question can only be achieved with more research into the relationship between the vertical distribution of lidar and forest canopy structure. Providing the relationship can be understood, the opportunity exists to use lidar-based empirical distribution functions to model aboveground biomass change through time.

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THE CAPABILITY OF HELICOPTER-BORNE LASER SCANNER DATA IN A TEMPERATE DECIDUOUS FOREST

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ABSTRACT

Helicopter-borne laser scanner data with high sampling density of different seasons were compared to investigate the capability in generating DEM (digital elevation model) and canopy stratification and understory vegetation were extracted from them in a temperate deciduous forest. The laser scanner data were acquired on 24 August 2001 in a full-leaf season and 14 April 2002 in a leafless season with sampling density of more than 25 points/m^2. The DEM for the study plot was generated from the last pulse data of the leafless season after removing noise data reflecting from branches, stems and understory vegetation. The transmittances through canopy layers and understory vegetation of the last pulse data in the leafless season and the full-leaf season were calculated. As a result, their transmittances were 20 % and 69 % respectively. These indicate the overwhelming advantage of the data in a leafless season to generate DEM in a temperate deciduous forest. The three-dimensional structure of canopy stratification and understory vegetation were extracted by assuming a series of adjoining spaces with 1 meter wide along a certain direction in the study plot. Whole laser scanner data within each space were projected to a corresponding vertical plane to comprehend the canopy stratification and distribution of understory vegetation. Scattering points on a vertical plane shows canopy layers, understory vegetation and the ground. From a series of vertical planes, we could identify the structure of canopy – understory vegetation – topography as well as the gap structure.

INTRODUCTION

Observation with remotely sensed data is effective for forest monitoring widely and many methods for monitoring and forest inventory have been developed for the last several decades. In spite of its advantages, however, there is a limit to conventional remote sensing for forest inventory because of acquisition of two-dimensional information. Lidar (light detection and ranging) remote sensing is an expansion from two-dimensional observation to three-dimensional measurement and we expect to improve accuracy of estimate on potential of productivity and biomass through acquisition of data about height. There has been growing interest in the utilization of lidar remote sensing in forestry.

The studies on application of airborne laser-profiling systems to forestry were started in 1980s (Maclean and Krabill, 1986; Nelson *et al.*, 1988). They recognized the powerful potential in those days, however, its practical use has been restricted for a long time because of limitations with measuring instruments and the lack of computer capacity for calculating and analysing the huge amount of measurement data. Airborne laser scanning systems are now available to extract three-dimensional structure of forest stand. Advance of the GPS and the inertial measurement unit (IMU) has made it possible extract stand parameter such as mean height, mean diameter at breast height (DBH), stand volume statistically (Nelson, 1997; Næsset, 1997a; Næsset, 1997b; Magunussen and Boudewyn, 1998; Magunussen *et al.*, 1999; Means *et al.*, 2000). Recently, studies concerning forest lidar remote sensing seem to be divided into two streams. One is about its practical use and evaluation of cost-performance in forest inventory (Lefsky *et al.*, 2001; Næsset, 2001; Næsset, 2002) and the other is concerning direct observation of individual trees with high sampling density for ecological approaches. As a pulse repetition frequency has increased rapidly, observation using a laser scanning system expands stand characteristics to measurement of individual trees (Hyyppä *et al.*, 2001; Persson *et al.*, 2002; Brandtberg *et al.*, 2003; Hirata *et al.*, in press).

Lidar remote sensing is very useful for ecological studies because three-dimensional canopy structure for evaluating forest functions can be measured (Lefsky *et al.*, 2002). The measurement by helicopter-borne laser scanning system has two advantages compared with airplane-based measurement. One is the flying altitude and the other is the flying speed. These advantages result in smaller footprints and shorter distance between neighbouring footprints. This distance becomes more significant when the canopy structure has complex stratification (Hirata *et al.*, 2003). A mixed deciduous forest normally has several layers. This study aims to compare the transmittances of laser in a full-leaf season and a leafless season for generation of DEM and extract a canopy – understory vegetation – topography structure in a temperate deciduous forest.

METHODS

Study plot

This study was conducted in the 6-ha permanent plot in the Ogawa Forest Reserve at the southern end of Abukuma Mountains, central Japan (36°56' N, 140°35' E, 610 - 650 m above sea level). The mean annual temperature is 9.0 °C, with the highest monthly mean of 20.5 °C in August and the lowest one of –1.6 °C in February. Annual precipitation is about 1750 mm, concentrated in August and September, and there is little rainfall in December and January. Maximum snow depth is occasionally 50 cm in winter, but it usually melts away in a few days. The forest has been protected from human impact for 80 years or more. There are more than 50 woody species in it, dominated by *Quercus serrata* Murray, *Fagus japonica* Maxim., and *Fagus crenata* Blume. Detailed delineations of the stand structure and dynamics of the community are available in Masaki et al.. (1992), Nakashizuka *et al.*. (1992), and Abe *et al.*. (1995).

All trees with more than 5cm DBH in the 6 ha plot were identified, tagged and mapped. We recorded the DBH of all trees. Litter traps have been set up with every 10-meters interval in the 1.2 ha core area within the plot. For all trees over 5 cm DBH in a half of the core area, tree height and the coordinates of top and base were measured.

Laser scanner data

The ALMAPS (Asahi Laser Mapping System), which consists of the ALTM 1225 laser scanning system produced by the Optech, Canada, the GPS airborne and ground receivers, and the inertial measurement unit (IMU) reporting the helicopter's roll, pitch and heading, was used to acquire the laser scanner data. The laser scanner transmits the laser pulse at 1064 nm (near-infrared) and receives the first and last echoes of each pulse. The elapsed time is measured to calculate the distance between the scanner and the object.

The laser scanner data were acquired on 24 August 2001 and 14 April 2002. The flight altitude of the helicopter above the ground was about 250 meters and the average of the flight speed was approximately 14 m/sec. The pulse repetition frequency was 25 kHz and the scan frequency was 25 Hz. Maximum scan angle (off nadir) was 12°. The beam divergence was 1.0 mrad. Overlap of scanning between neighbouring flight lines was about 50 %. Sampling densities of two different times were 25.0 points/m^2 and 31.9 points/m^2 respectively. Therefore, the footprint diameter was approximately 25 cm and the distance between neighbouring footprints was less than 20 cm. Both first pulse and last pulse were acquired to extract forest canopy and topography in rugged terrain.

Data analysis

Post-processing for the LIDAR data was performed to correct aberration. A DEM with 25 cm ground resolution for the study plot was generated from the last pulse data of the leafless season after removing noise data reflecting from branches, stems and understory vegetation. Minimum value was extracted in every 0.25 m^2 and extreme values were removed comparing neighbouring ones.

We compared transmittances of laser through canopy in a full-leaf season and a leafless season to evaluate the capability in generating DEM from last pulse data of both seasons. Transmittances through of last pulse data in a full-leaf season and a leafless season were calculated using the threshold of less than 1meter above the ground.

Next, we assumed adjoining spaces with 1 m wide along a certain direction in the stand and whole measurement data within each space were projected to a corresponding vertical plane to recover a canopy structure. Scattering points in a vertical plane showed multiple layers of a forest canopy within a corresponding space. A series of projective planes of measurement data for each plot was prepared to verify stratification.

RESULTS AND DISCUSSION

After post-processing for acquired data, 3-D models concerning forest canopy surface and topography were generated from both first and last pulse data (Figure 1). A fine DEM with 25 cm ground resolution was generated from the last pulse data of the leafless season after removing noise data (Figure 2).

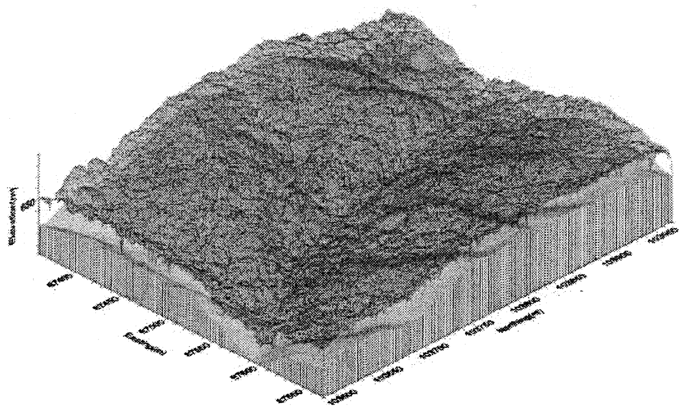


Figure 1: 3D models from first and last pulse data

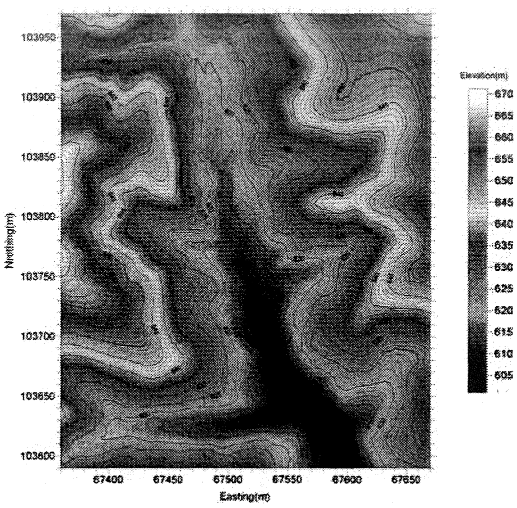
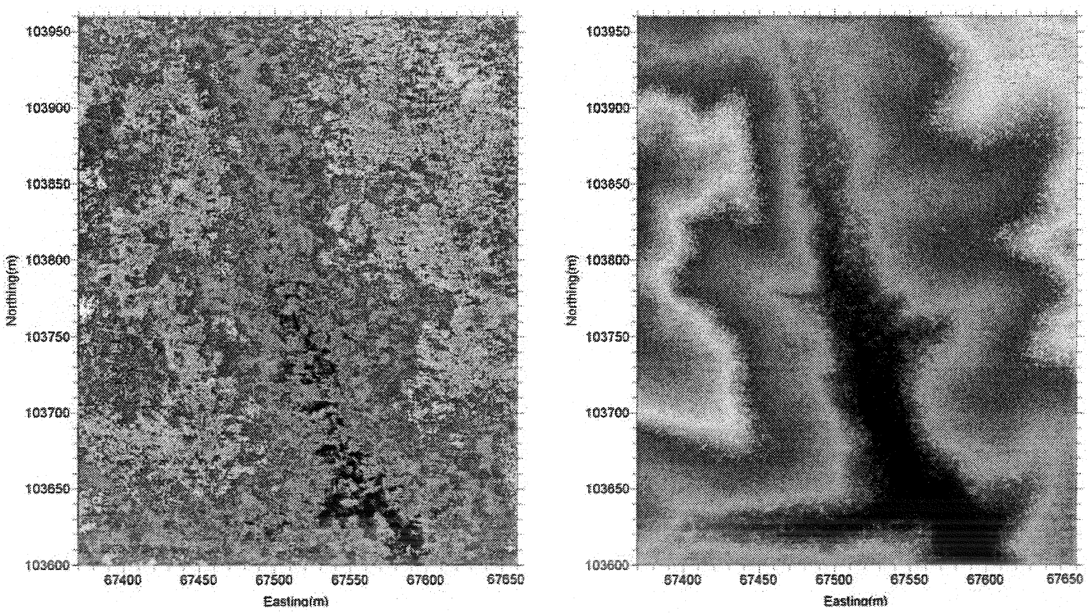


Figure 2: The DEM for the study plot

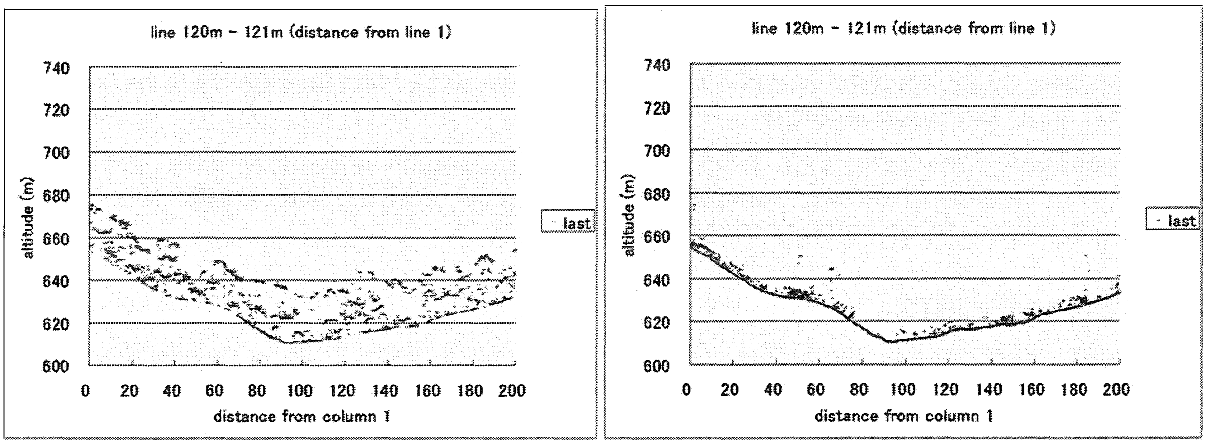
Figure 3 shows the last pulse data in the full-leaf season and the leafless season to understand the difference of transmittance between them. Figure 4 shows the vertical planes where the whole last pulse data in the full-leaf season and the leafless season within 1 meter wide were projected. Dense scattering points of the right figure (in the leafless season) represent the ground elevation. We see from these figure that it is important to consider the time of data acquisition to generate accurate DEM.

The transmittances through canopy layers and understory vegetation of last pulse data in the leafless season and the full-leaf season were calculated in every 1 m^2. As a result, their mean transmittances were 20 % and 69 % respectively. We saw that even last pulses were reflected by foliages in full-leaf season in a temperate deciduous forest. Therefore, measurement points where the laser pulses transmit through canopy layers to the ground were found around crowns of trees. These indicate the overwhelming advantage of the data in a leafless season to generate DEM in a temperate deciduous forest.



in the full-leaf season *in the leafless season*

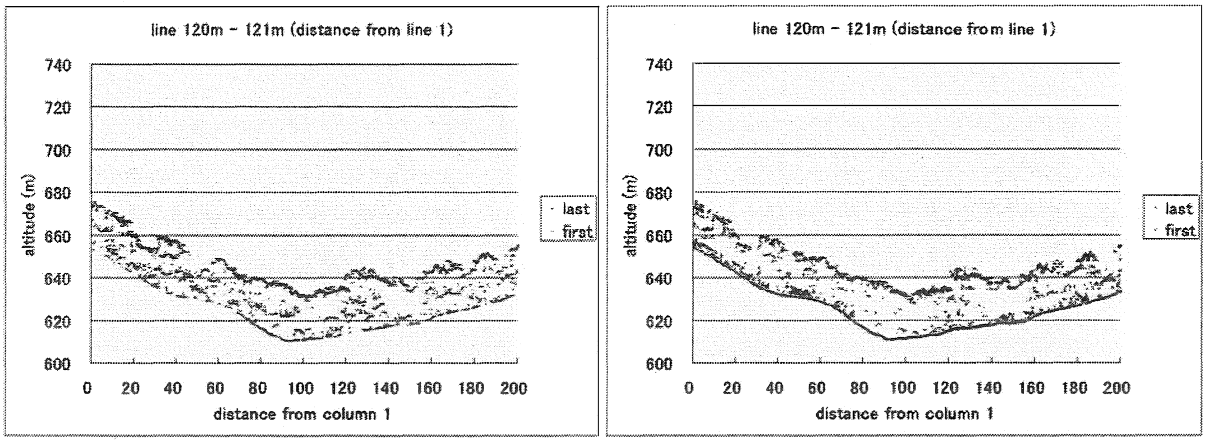
Figure 3: Comparison of the transmittances from the last pulse data between the full-leaf season and the leafless season



in the full-leaf season in the leafless season

Figure 4: Vertical planes where the last pulse data within 1meter wide were projected

The three-dimensional structure of canopy stratification and understory vegetation were extracted by assuming a series of adjoining spaces with 1 meter wide along a certain direction in the study plot. Whole laser scanner data within each space were projected to a corresponding vertical plane to comprehend the canopy stratification and distribution of understory vegetation (Figure 5). Scattering points on a vertical plane shows canopy layers, understory vegetation and the ground. From a series of vertical planes, we could identify the structure of canopy – understory vegetation – topography as well as the gap structure. We saw from this figure that both first and last pulse data in the full-leaf season were reflected the canopy surface or foliage, and only a weak pulse was returned from the ground surface. The first and second layers as well as gaps could be interpreted and distinguished from the measurement in the full-leaf season, but understory vegetation could not be identified. While this may cause us to underestimate stand density and overestimate stand height, it is nonetheless quite effective for estimating stand volume because small trees occupy only small part of the stand. On the other hand, understory vegetation and topography were very clearly identified from the both pulse data in the leafless season. We could understand the “canopy – understory vegetation – topography” structure from combination of lidar measurements of two different seasons.



in the full-leaf season   in the leafless season

Figure 5: The canopy – understory vegetation – topography structure from vertical projective planes of both pulse data

CONCLUSIONS

Stratification of canopy layers, distribution understory and topography is closely associated with the dynamics of a forest. This stratification could be extracted from laser scanner data with high sampling density. This analysis indicated that there are several opportunities to use helicopter-borne LIDAR measurement for ecological studies. As the canopy structure of a mixed deciduous forest is particularly complicated, its measurement requires quite small closely-spaced footprints. In addition, two measurements, one in summer and one in winter, can provide more are ecological information about a deciduous forest.

Forest conditions, such as species, forest patch size, topography where they grow, are quite different in each country. Therefore, suitable methodologies for applying lidar remote sensing to forestry have to be developed for respective forest conditions.

ACKNOWLEDGEMENTS

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LIDAR DERIVED 3D FOREST STAND PARAMETERS OF DUTCH PINE

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ABSTRACT

Forest inventory with traditional field measurements on a large scale is very time-consuming and expensive. Therefore, the last time a nation-wide Dutch forest statistics inventory was performed in the period1980-1983. Forest stand parameters that were described include dominant tree height, diameter at breast height, stem number, basal area, timber volume and forest structure (canopy gaps, canopy and shrub layers). These 3D forest stand parameters describe the internal dimensions of a forest stand.

LIDAR (Light Detecting and Ranging) is an active remote sensing technique that measures the height of the terrain. In The Netherlands, LIDAR is used for the construction of a nation-wide digital elevation model at 5-meter grid-level. In this paper a study is described that investigated the possibilities of LIDAR data to update Dutch forest statistics in an effective way.

For a study area near Wageningen, the Netherlands, aggregated LIDAR parameters at a 5x5-meter grid were computed for visualisation and quantitative analysis. At forest stand level the data were further aggregated for regression analysis with field data. Histograms of tree height at forest stand level were computed.

The results of this study showed the potential of LIDAR data to estimate 3D forest stand properties for large areas. The result of the regression analysis showed that LIDAR derived parameters were highly correlated with 3D forest parameters measured in the field. The aggregated LIDAR Height Dominant (LHD) parameter showed a good similarity with the measured dominant tree height (Hdom) for the selected homogeneous forest stands. The LHD parameter can be derived from the histogram of the forest stand heights. A map composition with an aerial photograph, several grid images, the forest stand height histogram and forest stand information is a valuable tool to interpret several LIDAR parameters at forest stand level visually.

INTRODUCTION

A forest stand is a parcel with uniform forest parameters. In the Netherlands it is usually even-aged with one dominant tree species. Forest parameters describe the actual situation of a forest stand (SBB 1988; Koop 1989; Stolp 1994). Dominant tree height, diameter at breast height, stem number, basal area, timber volume and forest structure (canopy gaps, canopy and shrub layers) are 3D forest stand parameters. These 3D forest stand parameters describe the internal dimensions of a forest stand.

3D forest stand parameters are valuable management information for forest owners, forestry policy decision-makers, forestry and climate researchers and the timber working industry. These parameters are usually acquired with field measurements at stand level or with sample points. However, 3D forest parameters change in time and they have to be updataed regularly through monitoring. Nation-wide acquisition of 3D forest parameters at forest stand level in The Netherlands has been performed 4 times in the past with a standard procedure for data acquisition. Forest Statistics 1939-1942 (Clement and Kooistra 2003) and Forest Statistics 1980-1983 are available in a geographic information system (Clement 2001).

Forest inventory with traditional field measurements on a large scale is time-consuming and expensive and for that reason the last time a nation-wide Dutch forest statistics inventory has been performed was in the period 1980-1983. At a nation-wide scale it can only be done with a sampling strategy like in the project "Meetnet Functie Vervulling" (Dirkse and Daamen, 2000, Dirkse *et al*

2001). This project has a larger goal than acquiring traditional forest parameters. The focus is monitor function fulfilling for forest and nature. For the selection of sample points a forest map was constructed using a land-use map in combination with the topographical map of The Netherlands. This forest map is not an update of the Forest Statistics 1980-1983 because of forest definition differences. Updating of Forest Statistics 3D forest stand parameters could be a complement to the "Meetnet Functie Vervulling" project used for future monitoring.

Potentially remote sensing is a powerful tool to observe forest stand parameters, especially LIDAR techniques. With a LIDAR (**LIght Detection And Ranging**) instrument from an aircraft or spacecraft a laser pulse is transmitted to an object. After the laser pulse hits an object the time delay of the reflection is measured by the sensor. With this time delay we know the distance between object and source. The location of the source and the direction and distance to the object are also known. Then a calculation can be made of the object location in X, Y and Z direction with a reliability depending on the used instrument and flight height.

A LIDAR footprint is the projection of the laser beam on the ground: a small footprint deals with a diameter of 0.2-1 meter, while for a large one it is 10-25 meter (Means, 1999). Most commercial LIDAR sensors are small footprint sensors because these sensors are more suitable for deriving a detailed digital terrain model. Large footprint LIDAR is in an experimental phase but with promising possibilities for measuring forest biophysical parameters (Lefsky et al., 2002, Drake et al., 2002).

Since 1995 laser-scanning techniques are operational on a large scale. With LIDAR the instrument scans a swath beneath the aircraft and collects many LIDAR hits of the surface. Several grid-based experiments have been performed to derive forest parameters (Hyyppä et al., 1999; Means 1999; Means et al., 2000, 2001; Naesset 1997a,b; St-Onge and Renaut 2001). These studies show that it is potentially possible to derive 3D forest stand parameters with LIDAR measurements, but there is no standard methodology available yet. In this study it was investigated how to obtain 3D forest stand parameters of Dutch pine from LIDAR.

The research questions of the study were:

1. What is the best way of visualisation of LIDAR data of a forest stand (vertical and horizontal height distribution) for the interpretation and classification of 3D forest stand parameters and selection for field work?

2. What are the relationships between LIDAR measurements and 3D forest stand parameters, in particular timber volume, for homogeneous Dutch pine forest stands as most common tree species in The Netherlands?

MATERIALS AND METHODS

The location of the study area is near Wageningen in the Netherlands (figure 1). The study area is 81 km^2 in size, of which 36.5 km^2 is covered with forest. The forests are located on the higher parts (30-75 meter above sea level) of the study area. The higher parts are glacial formed sandy plains with steep hills at the southern border.

The GIS of the latest forest statistics inventory (1980-1983) has been used to select homogeneous forest stands in the study area for further analysis and for aggregation of LIDAR data (figure 2). Aerial photographs were used to judge the pre-selected forest stands on homogeneity and canopy structure.

Top10-vector is the base-map with the topography in The Netherlands. This is a map based on black-and-white aerial photographs and field survey. For locating the selected forest stands on an overview map the 1:250.000 map has been used and for detailed studies the 1:10.000 map.

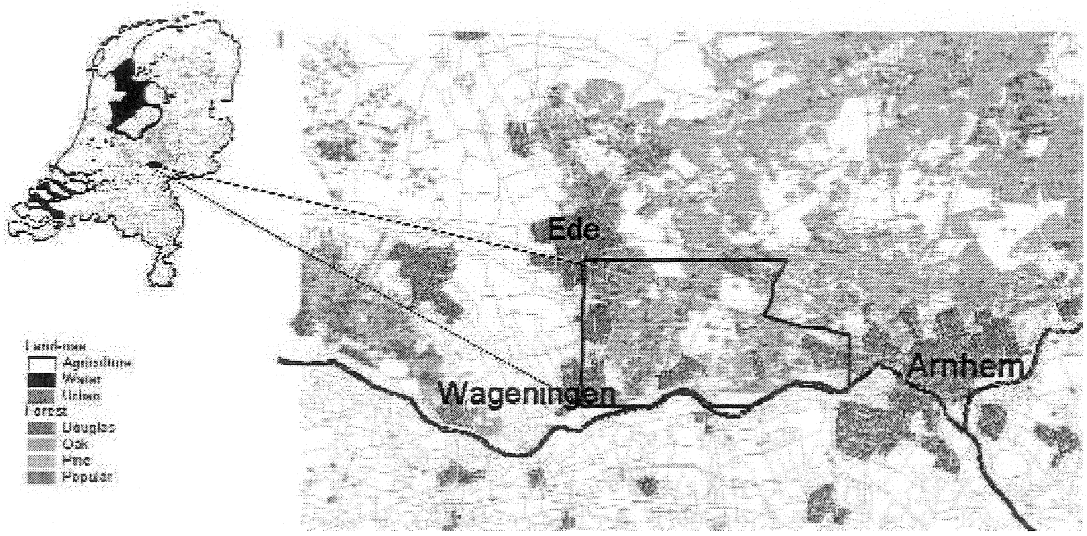


Figure 1: Location of the study area.

Figure 2: Left: map of the forest statistics from 1939 drawn on a topographical underground; Right: aerial photograph 2001 of same location. Both have on top the forest statistics 1980-1983 polygons in white.

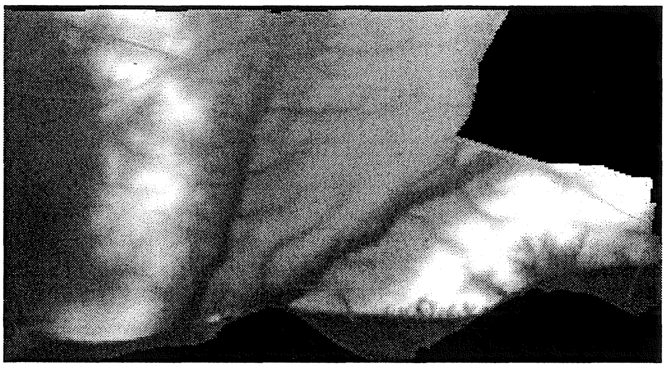


Figure 3: Digital terrain model of the study area near Wageningen.

The LIDAR data were specifically acquired to construct a digital terrain model (Heerd 2000). The data was delivered in ASCII format with X, Y, Z-values in two different data sets (two different flight tracks). The data acquisition period was March and April 2000, with an average of 2400 LIDAR hits per ha. Figure 3 shows an example of the digital terrain model.

Each LIDAR record was assigned to a 5x5 meter and 25x25-meter grid with a unique grid-id. With these unique grid-ids and the unique forest id-number new key-attributes were assigned to each LIDAR record. With these key-attributes it was possible to generalise the LIDAR data in grid-size windows within the forest stands. Each LIDAR data point with key-attributes was allocated to a grid-cell and to a forest stand. With this method grid-cells could be divided between two or more forest stands.

Several computer scripts were developed to derive appropriate aggregated LIDAR parameters at forest stand and at 5x5-meter grid level for visualisation and analysis purposes. A suitable grid size for aggregation and visualisation on a 1:10.000 scale was a 5x5-meter grid. With a 5x5 meter grid details in forest canopy structure and canopy gaps can be recognised as well as forest roads and forest stand boundaries.

After computing the DTM the distance of each LIDAR data point above ground level was computed and put in 1-meter height classes. Height histograms at forest stand level were computed. A height histogram is comparable with a "signal return waveform" (Drake et al., 2002) and can be described as a signal return of a single observation of a large footprint (10-25m) LIDAR trough a forest canopy. Therefore, these forest stand height histograms are displayed in the same way as the signal return waveform (see figure 4). Forest stand height histograms might deliver similar information as signal return waveforms.

Finally, statistics were determined. The following aggregated LIDAR parameters were computed on forest stand level:

- LHX = LIDAR Height MAX: maximum height per stand
- LHM = LIDAR Height Mean: average height per stand
- LHW = LIDAR Height Weighted, calculated as $\Sigma h^2/\Sigma h$ (according to Hyyppä *et al.*, 1999)
- LHC = LIDAR Height Crown: average of all hits > 2 meter above ground level
- LHD = LIDAR Height Dominant: LHC + 2x standard deviation
- LSC = LIDAR Soil Cover: percentage hits < 2 meter above ground level.

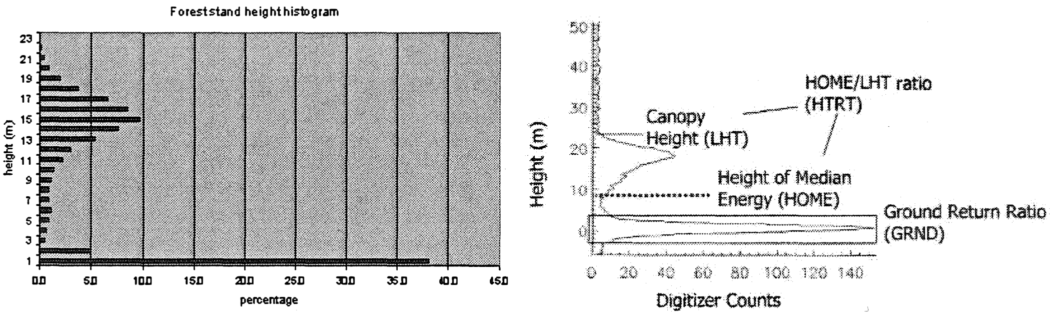


Figure 4: Forest stand height histogram (left) and signal return waveform (right).

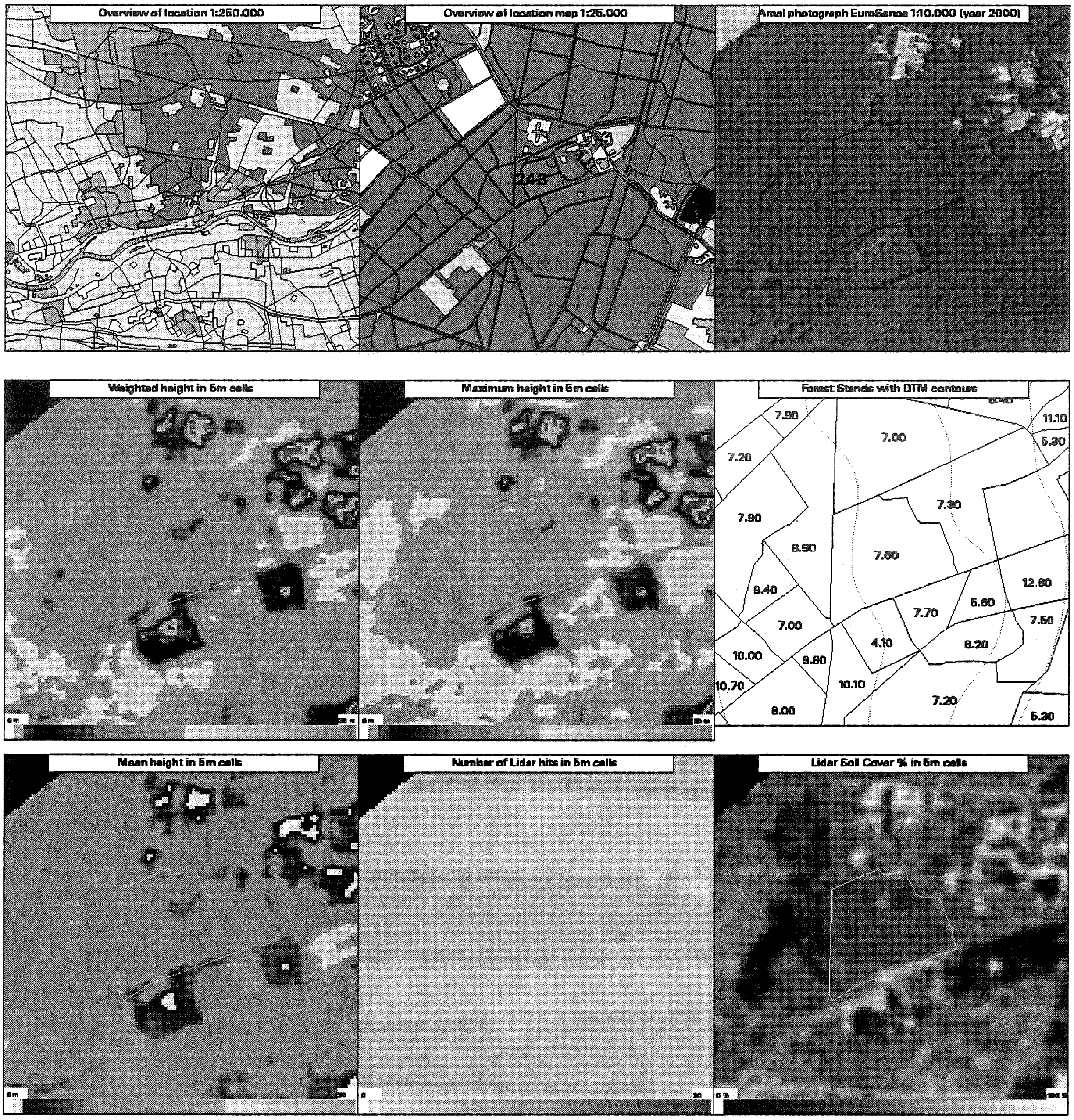
All forest stands in the study area were judged concerning homogeneity based on aerial photograph interpretation. A map composition with aerial photograph, several grid images, the forest stand height histogram and forest stand information was made to interpret the several LIDAR parameters at forest stand level. Moreover they were used to prepare the field survey. An example is presented in figure 5.

The criteria for selection of homogeneous forest stands were:

- Area should be at least 1 ha.
- Clear boundaries of the forest stands on aerial photographs.
- No large gaps in the canopy present.
- Only one canopy layer visible on the "forest stand height histogram".
- Forest stand should be located in a flat area.
- The stand should look spatially homogeneous on the four grid images.

For the selected forest stands a field survey was carried out in 2002 to estimate the actual 3D forest parameters. Timber volume (V02 in m^3 per ha), dominant tree height (HD02 in m), basal area (BA02 in m^2) and mean diameter at breast height (D02 in cm) were determined. Once the field data were collected and processed, statistical regression analysis with the LIDAR derived parameters at forest stand level has been applied.

Forest stand 243 with Dutch Pine



SPECIES	Dutch Pine
AGE	57
D82	16
V82	100
H82	13
LHX	15.2
LHW	13.2
LHC	13.2
LHM	7.6
LHD	20.1
LSC	43
D02	23
V02	350
HD02	21
BA02	34
S02	817

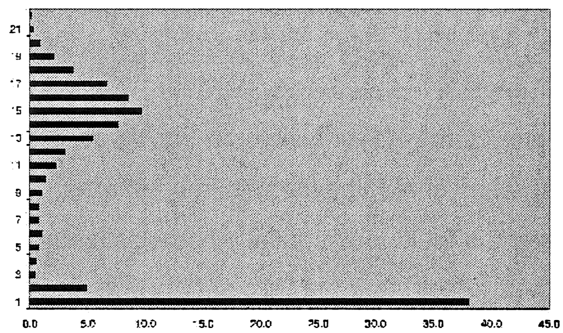


Figure 5: Forest stand report with several LIDAR derived grid images.

RESULTS

The number of Dutch pine forest stands measured in the field was 24. Linear regression models were applied (table 1).

Table 1: Coefficients of variation (R^2) between LIDAR derived and measured 3D forest parameters. Only significant values, when testing at a significance level of 5%, are shown.

Forest	LIDAR parameters					
3D parameters	LHD	LHX	LHW	LHC	LHM	LSC
V02	0.57	0.66	0.69	0.57	0.77	0.32
HD02	0.82	0.84	0.82	0.83	0.62	-
BA02	0.17	0.25	0.28	0.17	0.49	0.65

The LIDAR Height Mean (LHM) parameter shows the highest correlation with measured timber volume (V02) (figure 6: R^2 of 0.77). LHM describes the whole canopy: low values indicate open or low canopy and high values indicate a dense and high canopy. Hyyppä *et al.* (1999) found for the LHW parameter a higher correlation with timber volume than for the LHM parameter.

The LIDAR Height Dominant (LHD) parameter shows a good similarity with the measured height dominant (HD02) for Dutch pine forest stands (figure 7), while the mean height parameter used by Naesset (1997a) underestimates the ground truth mean height by 4.1 - 5.5 meter. In literature there is no (small footprint) LIDAR derived parameter described yet, which is directly comparable with the actual tree height. For large footprint LIDAR there is the signal return waveform and the first return delivers the tree height within the footprint area (Lefsky *et al.*, 2002). In this study it is shown that small footprint LIDAR can be used also to estimate tree height after statistical aggregation of LIDAR data.

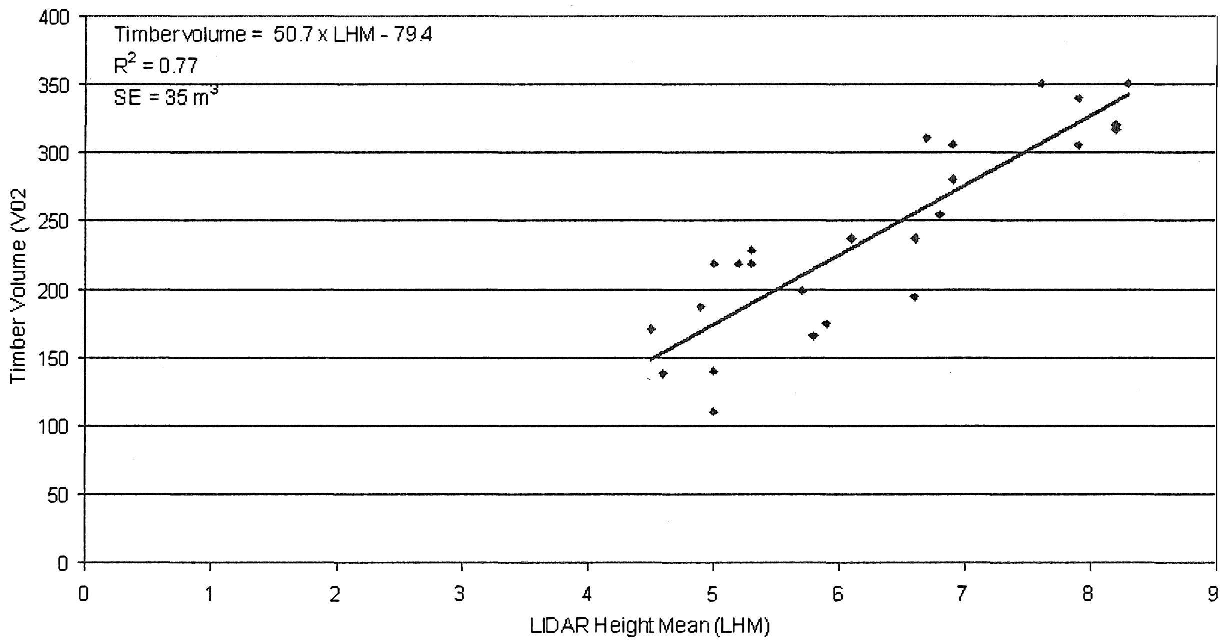


Figure 6: Graphical relationship between timber volume (V02) and LIDAR Height Mean (LHM).

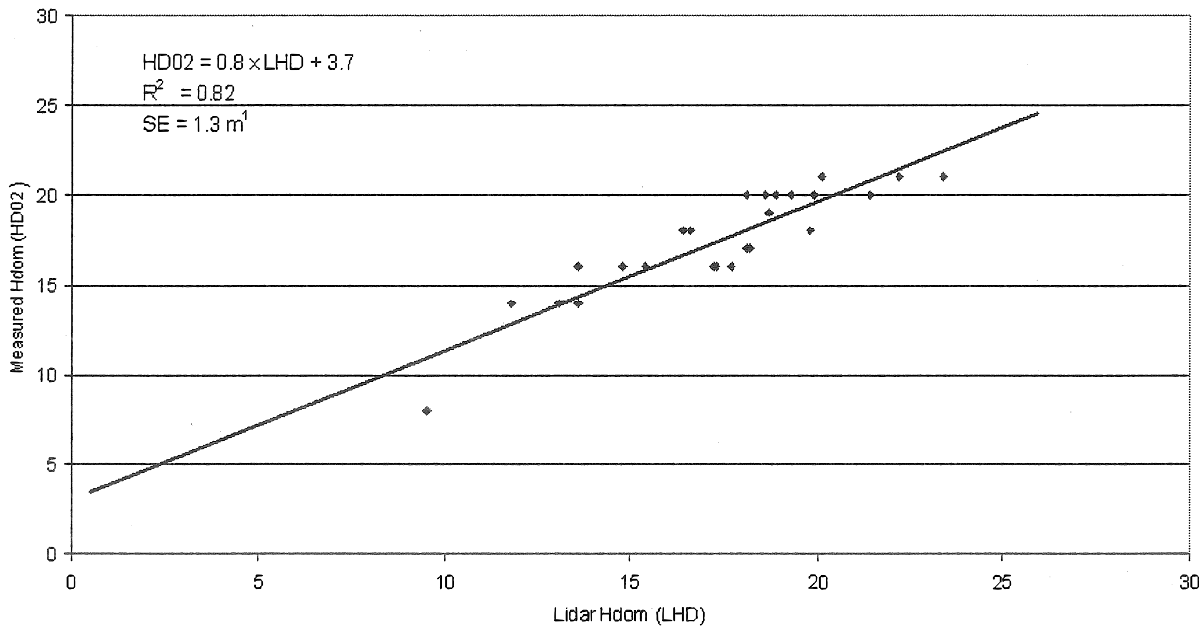


Figure 7: Graphical relationship between measured dominant tree height (HD02) and LIDAR Height Dominant (LHD). The line shows an almost one to one relationship because LHD is directly comparable with measured dominant height.

Another interesting relationship concerns the LIDAR Soil Cover (LSC) with the basal area (BA02). This relationship can be explained because with a thinned forest stand the signal can probe deeper into the canopy resulting in more ground hits. LIDAR Soil Cover (LSC) shows the highest correlation with basal area (BA02) (R^2 of 0.65). Naesset (1997a) used the mean canopy density, which is comparable with LSC, in a model to estimate timber volume. Means (2000) used the same approach and obtained high values for R^2. Means used the natural logarithm of the basal area and timber volume but in this study the results did not improve significantly using the natural logarithm.

Estimating actual tree height for Dutch pine yielded for all LIDAR parameters good results but the LHD parameter is more directly related. For timber volume a more sophisticated model could improve the results (Naesset 1997a,b; Means *et al.*, 2000, 2001). Multiple regression however, did not yield a significant improvement is this study.

CONCLUSIONS AND RECOMMENDATIONS

In this study the potential of LIDAR data to estimate actual 3D forest stand parameters for homogeneous Dutch pine forest stands is discussed. The results of the applied regression analysis are only valid for similar forest types and not for mixed or heterogeneous forest stands. The results of this study indicate the potential of LIDAR data to estimate 3D forest stand properties for large areas.

It can be concluded that:

1. The results of the regression analysis show that LIDAR derived parameters were highly correlated with 3D forest parameters.
2. Forest stand height histograms characterise the internal structure of a forest stand and were in agreement with the "signal return waveform".
3. The LIDAR height dominant (LHD) parameter has promising capabilities to estimate the actual (measured) dominant height of a forest stand.
4. The LIDAR Height Mean (LHM) parameter shows the highest correlation with measured timber volume on forest stand level.
5. Forest stand reports are very useful to obtain a first impression of the actual situation of the forest stand. This information is important to plan field survey.

Recommendations:

1. Model improvement to predict timber volume and other forest parameters, especially in the case of different tree species and heterogeneous forest stands.
2. To investigate how 3D forest stand parameters might be obtained for mixed forest stands.
3. To investigate how to derive LIDAR parameters of forest stands on steep hillsides.

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USING CROWN SURFACE MODELS FOR THE EXTRACTION OF FOREST INVENTORY INFORMATION: FIRST EXPERIENCES WITH STUDY AREAS IN STATE OF MECKLENBURG–VORPOMMERN (GERMANY)

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ABSTRACT

Cost-efficient provision of forest information is a central issue for the state forest service in Mecklenburg-Vorpommern. Standard mensurational attributes, such as tree height, dbh and number of stems continue to be important basis information for forest management planning.

In this paper the use of laser-data to estimate these attributes is tested and analysed, and first experiences are presented, where TopoSys GmbH laser data were used with 5 foot- prints per m².

- For *mean tree height* the "Weise´sche" top height was estimated (= mean height of the 20% tallest trees in the population/stand).
  Also, individual tree heights were derived.
- Mean *dbh* was then modelled as a function of "tree top surface" and tree height.

Field data are available for the study stand so that the accuracy of the predictions of stand and tree attributes could be checked. First experiences of this ongoing research show that the developed method allows approximating tree height, number of trees, dbh, and basal area such that they compare well to the terrestrially measured data.

INTRODUCTION

The state forest service needs precise forest inventory data for answering many forest related questions and to make use of it in the forest management. This data used to be terrestrially measured. Throughout the improvement of laser technology a forest inventory method has been developed which could give precise information about the forest and its structure.

During the process of developing this method it has become evident that information about single trees is often difficult to derive as ruling trees and dominated trees are hidden by dominant trees. And therefore they can hardly be detected. The spatial unit for all the following examinations is the single tree stand.

THE RESEARCH AREA

The examined area is situated in the southeast of Mecklenburg- Vorpommern in the forest district of Strelitz. The area is particularly interesting because of the high diversity of tree species and the strong growth. For the first examinations a nearly 30 year old stand of larch *(Larix decidua)* has been chosen. The stand parameters were terrestrially measured in the summer of 2002 and in February 2003 by means of a total inventory.

Table 1: Terrestrial data of the research are

Tree species	larch
Area size	0.914 ha
D_G (quadratic mean diameter)	26.53 cm
H_G (the height of the tree with the mean basal area)	23.89 m
B°	0.75
G (basal area)	17.13 m²
Number of trees	310

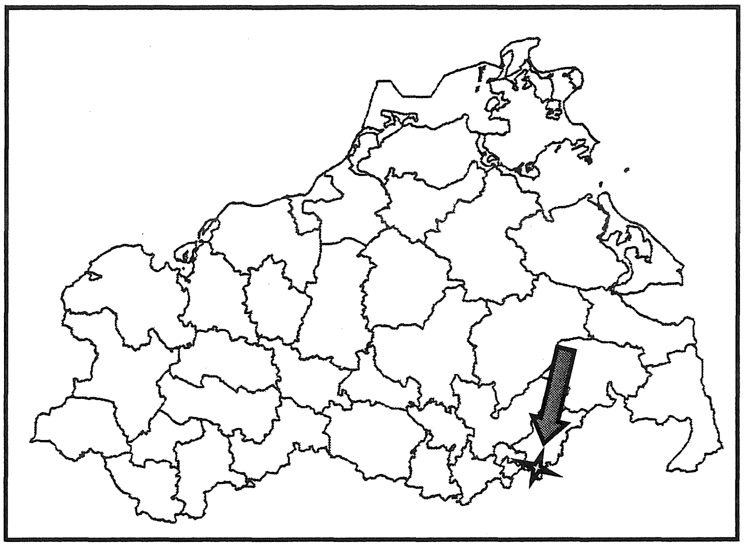

Figure 1: Location of the research area in Mecklenburg- Vorpommern (Germany)

LASER DATA

In April 2002 the first research area was scanned by an airborne LIDAR system of the Toposys Company.

Table 2: Performance parameters of TopoSys II (Lohr and Eibert, 1999; TopoSys 2002).

Sensor type	puls modulated laser radar
Scanning principle	fibre optic line scanner
Range	1600 m
Distance resolution	1.95 cm
Scan width	14.3°
Scan rate	653 Hz
Laser wavelength	1560 nm
Field of view	+/- 7°
Data recording	First and Last Echo, Intensity
Density of measure-points	5 per m²
Number of pixel per scan	127
Swath width (at 1000 m height above ground)	250m
Resolution of a distance measurement	< 0.03 m
Height accuracy of TopoSys DEMs	<0.15 m
Spectral channels	450 nm - 490 nm Blue
	500 nm - 580 nm Green
	580 nm - 660 nm Red
	770 nm - 890 nm Near Infra-Red

Last and first pulse raster data with a raster size of 1x1m have been provided. From a survey altitude of 1000 m the swath width on ground is about 250 m, the average measurement density is four to five measurements per m². Parallel to this laser data, pictures were taken with a four-channel line camera. The information content of these images has to be evaluated as not sufficient due to the date of data collection in spring time.

Processing of the data

The pixel of vegetation which can be found in the DTM (last pulse) ground data were eliminated by a filter method which includes minimum-detection, interpolation and thresholds.

The high points DSM (first pulse) were smoothed by Gaussian filter kernels. The intensity of filtering is determined by the standard deviation and it influences the tree height as well. As the smoothing is not dependant on direction, in the resulting image no artefacts can be found (Pinz 1994).

$$g(x,y,\sigma)=\frac{1}{2\pi\sigma^2}e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (1)$$

When taking the difference of the filtered DTM and DSM an absolute forest model or tree model is created.

Determination of stand extend with the help of auxiliary data (vector information)

For the further evaluation it is necessary to choose the stand units on which the evaluation should be based.

Due to the fact that a suitable algorithm is missing the stand borders are extracted from the existing vector data of the state forest service, so the following evaluation refers to single stands.

Extraction of inventory parameter

The knowledge of different forest key variables of the simplifies its management and makes it possible to describe the forest. Important parameters in this context are the tree height, the dbh, the basal area, the number of stems and the tree species.

Extraction of the tree height

From the tree model local maxima are chosen by means of simple filter algorithms and by including a certain number of neighbouring pixels. After the calculation of many different statistic values (e.g. mean value) in the course of the research the following method for the determination of the tree height with the help of the mean basal area has proven to be successful.

Derived from the well known "Weise'sche" top height (Kramer and Akça,1995) one calculates the mean value of the 20% of the highest data from the filtered data.

Quadratic mean diameter and the basal area of the complete stand

The dbh of a single tree cannot be derived directly from the tree model because of the crown overlapping.

One way to overcome this restriction is to regard the tree crowns as shapes of mountains. This means that the tops of the crowns are represented by the tops of the mountains and the transitions to the neighbouring crowns are shown as valleys. The area that is occupied by a "mountain" represents the crown surface area. Therefore, the correlation between the dbh and the crown surface area can be used for the calculation of the dbh.

$$kb_i = b_0 + b_1 \cdot d_i \qquad (2)$$

kb_i = *crown radius of the single tree*

d_i = *dbh of the single tree*

b_0, b_1 = *regression coefficients*

For all the existing tree species in the northern part of Germany the regression coefficients of many test stands have been determined in order to create the programme „BwinPro"(Nagel, 1999, 2001). Access to that data was given for the research on hand.

The crown surface area was segmented by means of a watershed algorithm. To achieve this aim, the tree model must be reflected over the crowns, so that the highest point in the original data becomes the lowest point after the reflection was done. In this method the borders of the crowns are represented as mountain ridges and by calculating the drainage basin they are vectorized.

The segmented areas can finally be used to calculate the dbh.

In the process of segmentation however, there occurs an overestimation of the crown surface area and consequently an overestimation of the dbh of the single trees. This problem results from the fact that the spatial density of trees often is very high so that no individual crowns could be developed and often two or three trees form a "single crown".

In order to minimize this error and to generate the actual dbh distribution, the following calculation methods are used.

From the already calculated dbh of the single trees a theoretical mean dbh (tD_G) is calculated.

After this a new dbh of the single trees is calculated. The non-linear statistic correlation between the dbh and the height of the stand, which can be represented in a height curve, served as the basis for the correction and derivation of the dbh. In Germany several standardised height curves for the reduction of height measurements required have been developed and those have been parameterised for the main tree species.

For the calculation relevant for the research on hand the standardised height curve according to GAFFREY (1988) was used, which includes the height of the tree with the mean basal area, the height of the single tree, the quadratic mean diameter and the dbh of the single tree. To get this result the formula was solved according to d_i and the dbh of the single trees were calculated.

$$h_i = 1{,}3 + (H_G - 1{,}3) \cdot e^{-(a_0 \cdot tD_g + a_1) \cdot (\frac{1}{d_i} - \frac{1}{tD_g})} \quad (3)$$

$$d_i = \frac{1}{\frac{\ln(\frac{(h_i - 1{,}3)}{(H_G - 1{,}3)}}{-(a_0 \cdot tD_G + a_1)} + \frac{1}{tD_G}} \quad (4)$$

h_i = *height of single tree*

H_G = *the height of the tree with the mean basal area*

tD_G = *theoretical* D_G

d_i = *dbh of the single tree*

a_0, a_1 = *regression coefficients*

The height of the single trees as well as the height of the stand was extracted from the LIDAR data. The overestimated tD_G is included as a weight for the specific characteristics of the stand. The crown surface area is influenced by the tree species, the handling of the stand, the stand density etc. These factors are not taken into consideration for the calculation of the crown surface area / dbh. From this newly gained data the basal area of the stand is deducted.

$$G_i = \frac{\pi}{4} * d_1^2 \quad (5)$$

With the above described method only a part of the stand is represented, however it represents an image of the real stand. This gets evident because of a small basal area of 13.69 m² as opposed to the terrestrial basal area of 17.13 m² and this is underlined in figure 2. Here the dbh distribution of the terrestrial total enumeration and the dbh distribution detected by the LIDAR scanner are shown. The eloping trees in the maximum area starting at 40 cm are caused by crown segments which are formed by groups of trees that grow very closely and therefore they are highly overestimated.

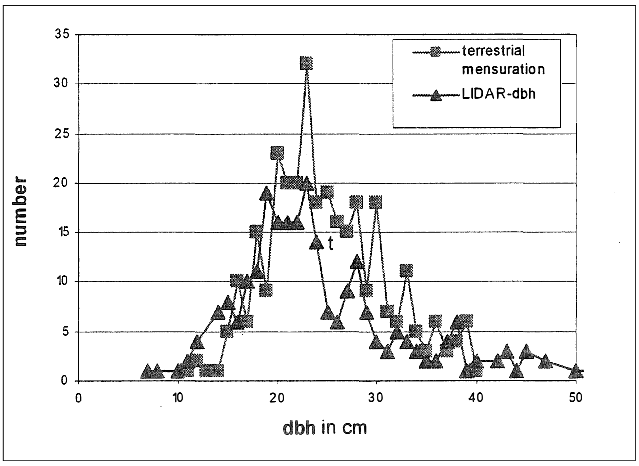

Figure 2: Description of the dbh distribution of the test stand and the dbh distribution after the second derivation

In order to find out the real stem number in a stand the formula for the basal area was employed without the constant $\pi / 4$.

$$G = \sum G_i$$

G_i	= *basal area of single tree*
G	= *basal area*
d_i	= *dbh of the single tree*
N	=*number of trees*

(6)

During the examinations it became clear that this constant equalizes approximately the amount by which the basal area was underestimated in the evaluation. With the aid of an estimated basal area, now the number of individual stems in a stand can be estimated by using formula (7).

$$N = \frac{40000 * G}{\pi * d_i^2} \qquad (7)$$

To conclude from the part of the image of the stand to the actual distribution of stand dbh, one will have to correct the frequency distribution of the dbh with the newly determined number of individuals.

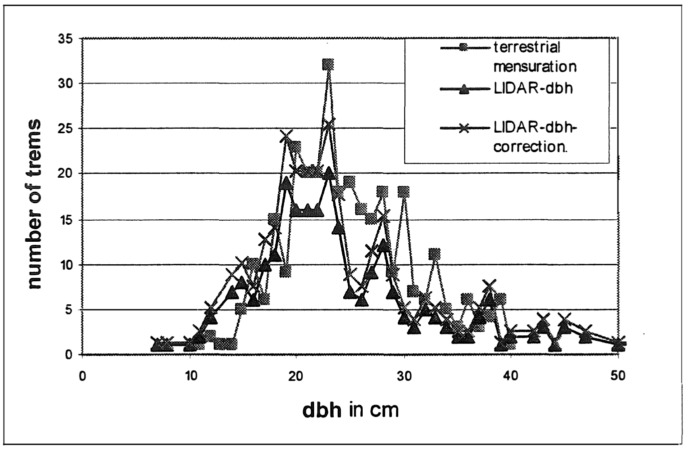

Figure 3: Description of the dbh distribution of the test stand and the dbh distribution after the second derivation and the correction of the stem number

As well as for the tree height, the estimation accuracy of dbh, basal area and stem number in a stand highly depend on the quality of the used DTM and the standard deviation of the filtering of the DSM.

RESULTS

While examining a thirty-year-old larch stand, the height of the tree with the mean basal area, which represents an important factor in the context of estimating the quality of a stand, could be determined. The height of the tree with the mean basal area (23.89 m) which was gained through a terrestrial total inventory could be calculated from the LIDAR data with the following method: extraction of the local maxima and the calculation of the mean values of the 20% of the highest points of this extraction. As can be seen from the table 3, the results highly depend on the quality of the DTM and the degree of smoothing of the DSM (Gaussian filter kernels). For the evaluation of the results the gained accuracy and the amount of errors should be seen in relation to the variation of the results of the terrestrial height measurements.

Table 3: Change of the stand height by use of different filter and detection parameters

Standard deviation (σ) with filtering of the DSM	Numbers of neighbours consider in detection of the local maximum	Filtering of the vegetation in DTM	Height of single tree (hg)	Number of stems N
no filtering	4	no	23.27	469
no filtering	4	yes	23.70	438
0,3	4	no	23.25	456
0,3	4	yes	23.71	415
0,4	4	no	23.25	369
0,4	4	yes	23.79	338
0,5	4	no	23.01	327
0,5	4	yes	23.61	292
0,6	4	no	23.43	247
0,6	4	yes	22.85	272
0,6	8	no	21.15	216
0.6	8	yes	23.09	208
0.6	24	no	23.70	149
0.6	24	yes	23.13	153
0.9	4	no	23.18	197
0.9	4	yes	22.48	239

The quadratic mean diameter of a stand could be determined with sufficient accuracy after using the segmentation of the crown surface area with the watershed algorithm, and also by means of the described second derivation with the simple correlation between the dbh, the crown surface area and the standardised height curve. As can be seen in table 4, the difference between the terrestrially gained DG and the DG from LIDAR data is smaller than one mm. If the formula (6) is employed, the basal area of the stand is 17.44 m² and varies only a little from the actual basal area (terrestrial inventory = 17.13 m²).

From the corrected basal area the number of stems could be estimated. The estimation showed 313 trees in the area, which means that it differed by three stems from the actual area (terrestrial inventory).

After having corrected the dbh distribution with the estimated number of stems, the changed dbh distribution nearly describes the same shape as the terrestrial one (see figure 3). Minor differences in the frequency can be observed in the dbh range between 24 and 27 cm and in the maximal frequency. The difference cannot be found in a varying frequency class, but in the number of values in the class. The maximal frequency for terrestrial and LIDAR data is 23 cm and it varies only with the number of individuals in the class.

Not only the stand height but also the dbh, the basal area of the stand and the number of stems are strongly influenced by the quality of the initial data.

Table 4: Comparison of the results of the survey by means of different filter and detection parameters

Data	05-04-1 (filtering of the DSM with σ = 0.5, detection of the local maximum with 8 neighbours, filtering of the vegetation in DTM)	05-04 (filtering of the DSM with σ = 0.5, detection of the local maximum with 8 neighbours)	Dabelow (terrestrial mensuration)
D_G	26,62 cm	24,79 cm	26,53 cm
H_g	23,62 m	23,10 m	23,89 m
N	246	255	310
N (formula)	313	324	
G	13,69 m²	12,15 m²	17,13 m²
G (estimated)	17,44 m²	15,67 m²	

CONCLUSIONS

The first results reveal that by using the described method the mean height of the stand, the quadratic mean diameter, the basal area and the number of stems can be determined with the necessary accuracy for the forest inventory. As opposed to works by Nilsson (1994), Næsset (1997), Ziegler *et al.* (2001), the aim of this study was to determine the stand parameters directly. This procedure has got the advantage that not all the individuals have to be detected. Furthermore, a direct comparison with single trees in the area is not necessary, which would be very difficult as the survey of the crown tops is not easy and very time-consuming.

Another aspect that still has to be critically observed is the use of the constant $\pi / 4$ for the basal area estimation. This constant serves as a correction factor for the underestimation of the number of stems, because of the fusion of crowns in very dense stands, and it is dependant on the stand density and the respective trees species. This method like any method needs to be verified in further test stands and if necessary it has to be modified.

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COMBINATION OF SINGLE TREE LASER SCANNING AND THEORETICAL DISTRIBUTION FUNCTIONS IN THE ESTIMATION OF PLOT VOLUME AND NUMBER OF STEMS

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ABSTRACT

Laser scanners of small footprint diameter and high sampling density provide wide possibilities for different forestry applications. They offer the possibility to obtain accurate height information on the forest canopy. In addition, when applying tree crown segmentation methods, individual single trees can be recognised and tree height as well as crown area can be detected. Underestimated tree heights are corrected to correspond to the tree heights measured in the field, i.e. an additional height calibration model is used.

The tree crown segmentation method used cannot detect suppressed trees from a height model based on laser scanning. Consequently, the shortest trees of the dominant tree layer may not be recognised. However, these trees can be predicted by using theoretical distribution functions. In this study, two different methods are used to predict small trees. In the first method, the parameter prediction method is utilised with the complete Weibull distribution, the parameters of which are predicted with separate parameter prediction models; thus, small trees are determined from the predicted tree height distribution. In the second method, the two parameter left-truncated Weibull distribution is smoothed to the detected tree height distribution. For the calculation of plot volumes, individual tree volumes are predicted by using the existing national volume models, which are based on the diameter at breast height and total tree height. However, before the volume models can be applied, diameters at breast height are needed for all trees. They are calculated from the diameter prediction model, the independent variables of which are the tree height and crown area or the tree height only.

INTRODUCTION

The use of different remote sensing materials in forest inventories has in recent decades become a realistic alternative. In Finland, satellite images are used in the multi-source National Inventory as auxiliary material (Tomppo 1993), whereas aerial photographs are in operational use in inventories by compartments to delineate stands and update changes (e.g. Anttila 2002a). In Norway aerial photographs have been used as a main information source in forest inventories (e.g. Næsset 1995, 1996).

The main problem concerning the use of spectral value-based remote sensing methods has been that the accuracy of the results has not usually been found to be on a satisfactory level. According to Tokola and Heikkilä (1997), reliable estimates of stand characteristics can be obtained using Landsat TM satellite images for areas larger than 150 ha. However, for single stands or forest estates remote sensing-based estimates have usually been inaccurate. The accuracy is also dependent on the resolution of the images. In recent Finnish studies the prediction accuracy of stand volume has varied from 30 to 40 % (Anttila 2002a, Anttila 2002b, Anttila and Lehikoinen 2002, Hyvönen 2002). The methods examined included visual interpretation and single tree pattern recognition of digital aerial photographs and non-parametric generalisation of stand characteristics based on characteristics of both digital aerial photographs and satellite images.

One specific problem when utilising spectral values of remote sensing images is the saturation of forest reflectance (Nilson and Peterson 1994). After canopy closure the observed spectral values do not considerably change although the amount of tree stock increases. Therefore, the results are more likely underestimates when obtained for stands that are maturing or at the stage of maturity (see, for example, Ardö 1992, Trotter et al. 1996).

One solution to the saturation problem is to consider the physical properties which are directly related to single tree dimensions. In such cases, estimates of tree heights can be produced by using several digital aerial photographs and 3-dimensional matching approaches (e.g. Korpela 2000, Gong et al. 2002). However, it is more likely that utilise airborne scanning laser (LIDAR) would be used.

Airborne lidars (profiling systems) have been used already in the 1980s to predict stand characteristics (e.g. Nelson et al. 1988). However, when using scanning sensors of small footprint diameter (10 to 30 cm) it is possible to get accurate height information on the forest canopy (e.g. Næsset 1997a, b, Magnussen and Boudewyn 1998, Magnussen et al. 1999, Means et a. 2000). Numerous studies have then indicated that, for example, mean height (e.g. Naesset 1997a, Magnussen and Boudewyn 1998) basal-area (e.g. Lefsky et al. 1999, Means et al. 2000, Naesset 2002) and stand volume (e.g. Naesset 1997b, Means et al. 2000. St-Onge and Renaud 2001) can be predicted accurately by using laser scanning.

Magnussen et al. (1999) proposed that if 6-10 laser hits per tree crown are obtained, individual trees may be detected; this was first demonstrated by Brandtberg (1999) and Hyyppä and Inkinen (1999). For example, in the study by Hyyppä and Inkinen (1999) the number of laser pulses was increased to more than 10 measurements per one square metre to recognise individual trees. Recently, St-Onge 2000, Gougeon et al. (2001), Hyyppä et al. (2001a), Lim et al. (2001), Magnussen et al. (2001), Persson et al. (2002), Popescu et al. (2002), Holmgren et al. (2003) and McCombs et al. (2003), among others, have used laser scanning or a fusion of laser scanning and different multispectral imageries to detect single trees. After preprocessing the data, single trees can be recognised by using different tree crown segmentation methods (e.g. Hyyppä et al. 2001a, Persson et al. 2002, Popescu et al. (2002, Holmgren et al. 2003).

In most of the studies on single tree laser scanning tree height is considered. However, it is also possible to calculate tree volume by using single tree models. Firstly, tree diameter is predicted by using tree height and segmented crown area (e.g. Hyyppä and Inkinen 1999, Persson et al. 2002) and, secondly, tree volume is calculated by using standard models, e.g. the functions of Laasasenaho (1982) in Finland. The obtained accuracy (RMSE) at the stand level has been slightly over 20 % (10 % if bias is not included (Hyyppä and Inkinen 1999)) for volume (Persson et al. 2002, Holmgren et al. 2003).

The common problem when using different individual tree recognition methods is that only the dominant tree layer is detected. Suppressed trees may not be found and the detection of the shortest dominant trees and tree groups is also difficult. This has caused the results to usually be underestimates. Even if the laser scanning produces information also under the dominating tree layers (e.g. Hyyppä et al. 2000b, Næsset and Økland 2002), the current segmentation methods cannot utilise it. In the study by Maltamo et al. (2003) a theoretical distribution function was combined with a diameter distribution estimate obtained from video imagery. The segmentation method found only large trees whereas small trees were predicted from the Weibull distribution obtained with the parameter prediction method. Diameters of large trees were calculated from segmented crown areas. The accuracy of estimated stand characteristics was improved considerably, especially in the case of number of stems.

This study examines the accuracy of single tree laser scanning used to produce estimates of plot volume and number of stems. These estimates are tested by using highly accurate field data and large mapped sample plots. The second objective is to combine a theoretical distribution function with the tree height distribution obtained with single tree laser scanning. Two well-known parameterisations of the Weibull function and two methods for the determination of distribution parameters, respectively, are used to predict heights of small trees: the two parameter Weibull with the parameter prediction method and the left-truncated Weibull distribution function with estimation of parameters from incomplete laser scanning data.

MATERIAL AND METHODS

Test site

The test site was placed in a state owned forest area of approximately 50 hectares located in Kalkkinen, southern Finland, 130 km north of Helsinki. The test site is rather hilly and is situated approximately 110 m above sea level. The main tree species are Norway spruce (50 % of volume), Scots pine (35 %), silver birch and downy birches (15 %). The tree stock of the area is naturally regenerated and there have been no silvicultural operations in most parts of the area during the last decades. Therefore, the tree stock can be considered to be in a semi-natural state. The test site has been used earlier for accuracy verification of different sources of remote sensing data (Hyyppä et al. 2000a). The correlation coefficients between remote sensing and field data were lower than in other corresponding studies, indicating that the area is difficult for remote sensing-based inventories.

Field measurements

During the summer of 2001 ten systematically located rectangular sample plots were established on the test site. The basic size of a sample plot was 30 m by 30 m, but to get around 100 trees per plot, plot sizes of 25 m by 25 m and 30 m by 40 m were also used. Most of the sample plots included dense understorey and were dominated by Norway spruce, although, each sample plot included more than one tree species. All trees having a diameter at breast height (DBH) of more than 5 cm were mapped and tree species, DBH, tree height, and height to the living crown were registered. Tree volume was calculated by tree species using the volume function of Laasasenaho (1982). Altogether 675 trees were measured. For example, volume and median height of the sample plots varied between 217-533 m^3ha^{-1} and 18-30 m, respectively.

For the construction of parameter prediction models of height distribution additional sample plot material, including 10 sample plots of the study material, was used. The additional plots were located nearby and measured in the same way as the study material. The total number of the sample plots was 33 comprising altogether 2700 trees.

Subsequently, the Global Positioning System (GPS) was used to determine the position of the four corners of each of the 10 sample plots. The coordinates of the corner points were measured by using a Leica SR530 RTK GPS system. RTK is based on the concept of relative GPS where two receivers, one at a reference point with known coordinates and one at a new point, simultaneously measure signals from the same satellites. Horizontal accuracy of the RTK measurements was verified to be approximately 0.015 m and vertical accuracy approximately 0.02 m in relatively open areas in another study (Bilker and Kaartinen 2001). If the RTK did not succeed in giving the corner points due to insufficient coverage of GPS satellites, a tacheometer was used to measure the corner points. It is expected that the corner points be measured with an accuracy better than 10 cm.

Laser scanning

The laser scanning acquisition was carried out on June 15, 2000 using a Toposys-1 laser scanner. The performance of the TopoSys-1 laser is depicted in Table 1 and the information can also be found at www.toposys.de. Three DGPS receivers were employed to record the carrying platform position: one on the aircraft, and two on the ground (the first as the base station, the second for backup). The test site was measured from an altitude of 400 m resulting in a nominal sampling density of about 10 measurements per one square metre. The survey altitude was selected to provide the number of pulses needed to resolve individual trees. However, the scanning mechanism of the Toposys-1 was not optimal, giving significantly higher pulse density in the flight direction than in the across-track direction. Due to the relatively low survey altitude applied, the swath width was approximately 100 m. First pulse data were applied since previous studies have shown that first pulse data can be successfully used for digital elevation model (DEM) generation in a boreal forest zone (Hyyppä et al. 2001a). The advantage of the Toposys-1 is its low scan angle, which is at maximum 7 degrees. Due to the overlapping of the nearby strips, the low scan angle provides a reasonably small amount of shadows. This results in high accurate DEM and in good geometric quality of the image.

Preprocessing of laser data

The data was calibrated with the calibration flight from cross-tracks over the Kalkkinen area. The captured data of the flights were transformed into the Finnish coordinate system KKJ-3. The systematic errors occurring in the transformation were corrected by using ground control points of summer cottages, road junctions and the base map. The height of road junctions were used to calibrate the terrain height and the planimetric calibration was performed with summer cottage outlines measured with 2-5 cm accuracy using RTK GPS and a laser distometer.

Table 1. TopoSys-1 laser scanner performance parameters

Parameter	Performance(s)
Sensor	pulse-modulated, TopoSys-1
Laser pulse frequency	83 000 Hz
Scan frequency	630 Hz
Field of view	± 7.1 degrees
Measurement density	4...5 per m^2 at 800 m
Number of shots per scan	128 parallel shots (one of which is the reference)
Swath width at 800 m	200 m
Position accuracy	x, y < 1.0 m
Elevation accuracy WGS84	z < 0.15 m
Laser classification	class 1 by EN 60825 (eye-safe)

The laser scanner survey provided a point cloud, in which the x, y and z coordinates of the points are known. The points of the first pulse data are reflected from the topmost surface, which can be terrain, vegetation or buildings. The digital surface model (DSM) was obtained by taking the highest value of all laser hits within each pixel (50 cm), and then interpolating the value for missing pixels. A corresponding approach has been used in the study by Popescu and Wynne (2003). By further processing the data and classifying the points to terrain and vegetation points, it was possible to produce a digital elevation model (DEM) and a digital tree height model (DTHM). The principle of preprocessing of laser data, detection of single trees and calculation of plot volume by using different approaches is also presented in Fig 1.

In order to generate the digital elevation model, DEM, from laser scanner data, the points that are reflected from non-ground objects, such as from trees and buildings, must be classified as non-ground hits. This was accomplished by a method developed at the Finnish Geodetic Institute (FGI) based on an algorithm of Ruppert et al. (2000). The general idea was to combine the high resolution digital elevation model, which was created by looking at the minima of all the laser measurements belonging to each pixel, with a low resolution one for identification and removal of non-ground points. This combination can then be repeated as frequently as it is necessary to generate a DEM of the desired resolution. The procedure starts with a coarse resolution. Iteratively, the resolution is improved until the desired resolution is reached, and a rough ground surface is created. This surface is usually lower than the real surface, especially in hilly areas, since a minimum value was taken for each DEM grid. Thus, a final refinement is performed to recover the original laser scanner data of the ground points by comparing the laser measurements with the corresponding values of the created surface and using them in the final interpolation of DEM. The accuracy of the DEM algorithm was tested by Ahokas et al. (2002), and in a hilly, forested environment an accuracy of 14 cm was obtained. The methods for calculating the DEM on forests is relatively mature, and even commercial software exist to perform the task, e.g. TerraScan by Terrasolid Ltd (Soininen 1999). It has been shown that the algorithm of the FGI for DEM is comparable in accuracy with the TerraScan (Ahokas et al. 2002), which is based on the method by Axelsson (1999).

The tree height model (DTHM) was computed as the difference between the digital surface model and the digital elevation model. An example of the final DTHM is presented in Fig. 2. The field measurements, rectified to the corresponding coordination system, are also presented. In a high resolution laser scanner image, individual trees are readily identifiable by a human interpreter as displayed in Fig. 2.

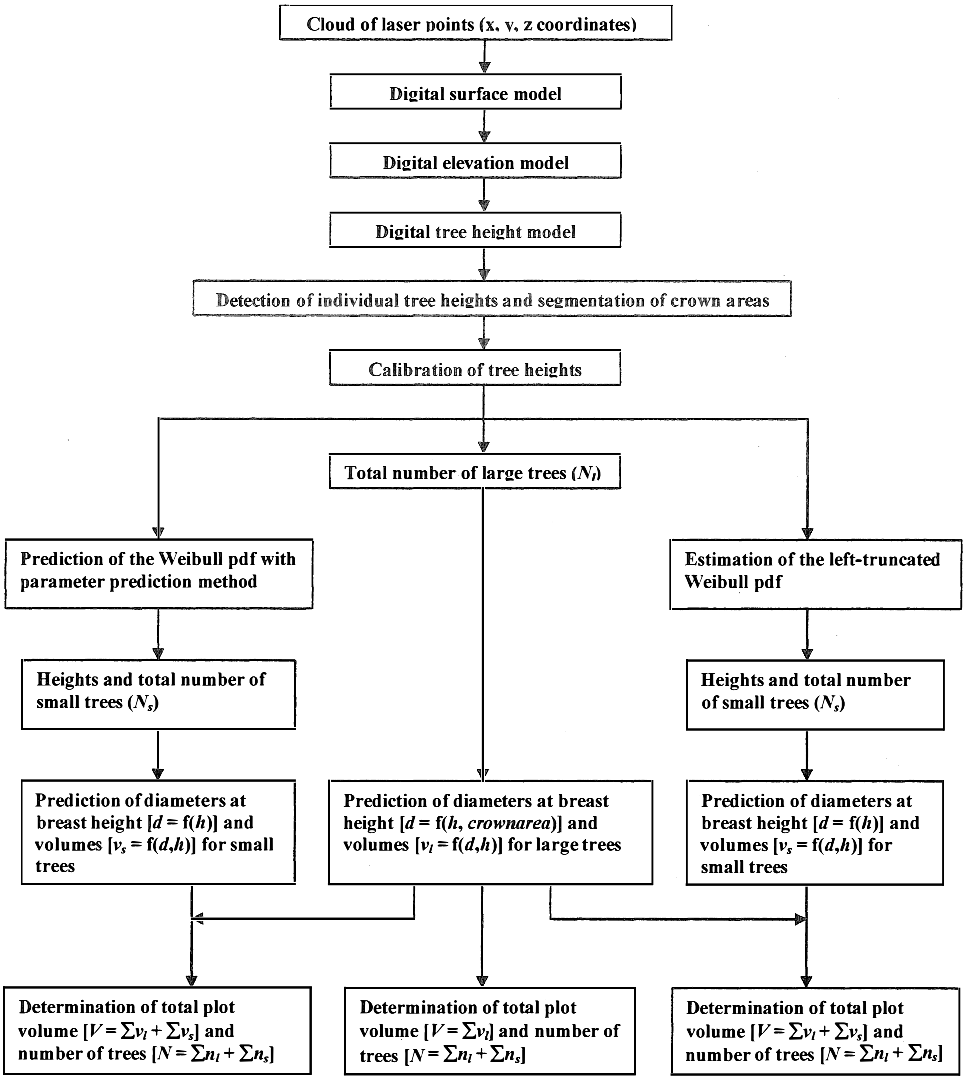

Fig. 1 The principle of the preprocessing of laser data, detection of single trees and calculation of plot volume using different approaches.

To get location and crown area of individual trees, tree crowns were segmented from the DTHM (see also Fig. 1) using a commercial software Arboreal Forest Inventory Tools of Arbonaut Ltd., which was originally developed for aerial photos and video images (Leppänen et al. 1999). In the software, segmentation of tree crowns consists of filtering, finding local maxima for seed points and seeded region growing segmentation (Maltamo et al. 2003). The laser-based algorithm is also depicted in Hyyppä et al. (2001a) and the performance of the segmentation algorithm compared to two other algorithms (developed at Joanneum Research in Austria and the University of Freiburg in Germany) is depicted in Hyyppä et al. (2001b) and in the final report of the EC-funded HIGH-SCAN project (Hyyppä and Hyyppä 2001).

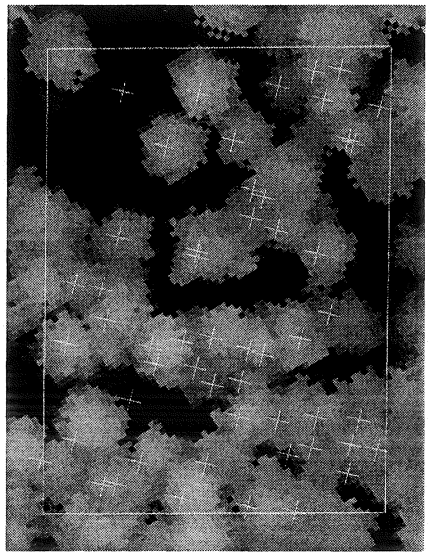

Fig 2. An example of the final DTHM in one sample plot.
Crosses indicate the locations of trees measured in the field.

To locate trees, the DTHM was low-pass filtered and searched for local maxima, whose positions were considered to be tree locations and seed points for crown segmentation. The estimates of laser scanning-based tree heights were then obtained from the unsmoothed DTHM. In the segmentation program, a local maximum was defined to be a pixel whose value is greater than the value of any of its eight neighbouring pixels, i.e. the size of the search window was 3 by 3 pixels.

The sample plots were processed separately to get an optimum result for each one, but in principle the method is extremely robust (see Hyyppä and Hyyppä 2001). In the laser inventory part of the Forest Inventory Tools of Arbonaut Ltd, you have three parameters: filterPar, describing the amount of filtering (the value 2 was selected in this study), area cutoff and seed threshold. The adjusting of the parameters is based on the visual checking of the tree detection and crown segmentation result. The amount of filtering affects to the number of local maxima, i.e., it decides in how many segments the image is split. The amount of filtering was selected to be as low as possible but large enough to prevent getting multiple maxima within clear individual crowns. Furthermore, it was expected that each segment would present the area of a single tree crown. The latter two parameters indicate the range of tree heights included in the analysis. Selecting the values 3 and 40 indicates that trees up to 40 m in height, the branches of which are higher than 3 m above the ground, are included in the segmentation.

Calculation of plot volume

When compared to the corresponding field measurements the result of the laser scanning and tree segmentation processes is a tree height which, unfortunately, is an underestimate for two reasons. The first reason is that laser pulses hit the topmost part of the tree, which is not the tip of the tree stem. The second reason is the time difference of about one growth season in the laser campaign and field measurements. Tree heights were corrected using a calibration model by Maltamo et al. (forthcoming):

$$\hat{h}_{\text{corrected}} = 1.871 + 0.963 \times h_{\text{laser}}, \tag{1}$$

where $\hat{h}_{\text{corrected}}$ is the estimate for the correct tree height (m), and h_{laser} is the tree height (m) obtained from the laser scanning data by using the tree crown segmentation method.

To be able to utilise volume functions, diameters at breast height were needed for all trees (see also Fig 1). For the determination of diameters at breast height a prediction model was constructed using tree height and segmented tree crown area as explanatory variables. Due to the spatially hierarchical correlation structures (sample plots, trees) of the study material, the basic assumption of the OLS estimation about noncorrelated residuals did not hold and a mixed modelling was applied in the estimation of linear prediction models (see, e.g., Searle 1971, Goldstein 1996). All laser detected trees, i.e. a total of 275, were used in the modelling. The laser-based trees were matched to the field trees by overlaying the locations of both on the DTHM and by linking each laser tree location visually to the nearest tree or one of the nearest trees. In the linking of the locations, laser derived heights could be used to select a matching tree of similar height to prevent the linking of, for example, a tall tree to an understorey tree.

Tree volumes were calculated using Laasasenaho's (1982) models for pine, spruce and birch. Independent variables of these models are diameter at breast height and total tree height. Due to a lack of tree species classification, different species were weighted by 1/3.

Modelling of the height distribution of small trees

The estimation of the height distribution of small trees was implemented with two separate methods. In the first method a complete two-parameter Weibull distribution was applied, whereas the second method was based on the application of the left-truncated two-parameter Weibull distribution. Respective probability density functions for the complete and left-truncated two-parameter Weibull distribution are as follows:

$$f(x) = \begin{cases} \frac{c}{b} \times \left(\frac{x}{b}\right)^{(c-1)} \times e^{\left[-\left(\frac{x}{b}\right)^{c}\right]}, & 0 \le x < \infty; b, c > 0 \\ 0, & x < 0 \end{cases} \tag{2}$$

$$f(x) = \begin{cases} \frac{c}{b} \times \left(\frac{x}{b}\right)^{(c-1)} \times e^{\left[\left(\frac{t}{b}\right)^{c} - \left(\frac{x}{b}\right)^{c}\right]}, & t \le x < \infty; b, c, t > 0 \\ 0, & x < t \end{cases} \tag{3}$$

where *x* is a random variable, i.e. tree diameter, *b* is a scale parameter, and *c* is a shape parameter. The distribution parameters of both Equations 2 and 3 were obtained by applying an iterative Maximum Likelihood (ML) estimation.

In the first method, the parameters of the distribution were estimated by smoothing it separately to entire height distributions of larger field data consisting of 33 sample plots. Parameters of the estimated distributions were regressed using characteristics of the height distribution. Observed maximum height and mode class of dominant tree layer of the height distribution were used; both the maximum height and mode class of dominant tree layer can be obtained from laser scanning. The first method corresponds to the method by Maltamo et al. (2003). Instead of modelling diameter distributions, this study modelled tree height distributions and the choice of truncation point was not fixed. Parameter prediction models were estimated using least squares estimators because this dataset did not contain hierarchical correlation structures; only one pair of *b* and *c* parameters was obtained for each plot.

In the application phase the parameters *b* and *c* were predicted using estimates of maximum height and mode class obtained from laser scanning. The value of the Weibull cumulative function was solved using a subjectively chosen height class of truncation point as a random variable. Subsequently, the total number of stems per hectare was calculated using information about the proportion of short trees and the estimated number of dominant trees obtained from laser scanning. For the calculation of volumes of short trees, a separate prediction model for diameter at breast height was constructed by using all 675 measured trees of the study material. The only explanatory variable of the model for diameter at breast height was total tree height. In model applications, diameters at breast height were predicted for the mean trees of 1-cm height classes obtained from predicted height distributions, after which stem volumes were calculated using volume functions.

In the second method, the left-truncated Weibull function was used to smooth out the sample plotwise height distribution data obtained from laser scanning. This was done separately for the 10 sample plots of the study material. Furthermore, sample plotwise values of the truncation point were chosen subjectively. The share of small trees was then calculated as in the first method. Instead of predicting parameters b and c, the original estimates for the parameters were used. This type of approach has previously been used, for instance, in the study by Zutter et al. (1986), which considered diameter data truncated at a specific threshold level. Truncated distribution functions have also been used, for example, in examining the height distribution of enlisted soldiers in relation to the population as a whole (Vuori 2002). The calculation of plot volume by using tree heights of individual trees, constructed tree models and distribution function approaches to predict small trees are presented in Fig. 1.

The criteria used in the comparison of the accuracy of predicted stand characteristics were the Root Mean Square Error (RMSE) and bias. The corresponding relative values were obtained by dividing the absolute value by the mean of the true value. In the study by Hyyppä and Inkinen (1999) standard error *(s_d)* of the estimates were used, i.e. systematic error was removed from reliability figures. Corresponding figures were also calculated in this study using the following formula:

$$s_d = \sqrt{RMSE^2 - bias^2} \qquad (4)$$

Although the dataset used was quite small, the reliability figures were calculated for the comparison of results between this and earlier studies. Furthermore, visual examinations were made.

RESULTS

The basic nonlinear form of the model for the diameter at breast height of tall trees is multiplicative. Due to the multiplicative form of model errors and in order to linearise the relationship between the dependent and independent variables, the basic nonlinear model was transformed into a linear form by taking a natural logarithm. Therefore it was possible to implement the estimation of model parameters with linear regression estimators. A mixed model for diameter at breast height is as follows:

$$\ln(d_{ij}) = \mathrm{p}_0 + \mathrm{p}_1 \times \ln(h_{\mathrm{corrected}\,ij}) + \mathrm{p}_2 \times \ln(crownarea_{ij}) + \mathrm{s}_i + \mathrm{e}_{ij} \qquad (5)$$

where d_{ij} is the diameter at breast height (cm) of tree *j* in the sample plot *i*, $h_{\mathrm{corrected}\,ij}$ is the corrected tree height (m) detected using laser scanning, $crownarea_{ij}$ is the area of the segmented tree crown (m^2), p_0, p_1 and p_2 are fixed parameters, s_i is the random sample plot variable $(s_i \sim \mathrm{N}(0, \sigma_s^2))$ and e_{ij} is the random error term $(e_{ij} \sim \mathrm{N}(0, \sigma_e^2))$. Because the measurements of the original field data were restricted to trees with a minimum diameter at breast height of 5 cm, the model is not valid for smaller trees than the selected threshold diameter.

As crown areas of short trees, i.e. trees that are obtained with the distribution-based methods, are not known, their diameters at breast height cannot be predicted using Equation 5. A specific model for the diameter at breast height of small trees is as follows:

$$\sqrt{d_{ij}} = p_0 + p_1 \times h_{\text{corrected}\,ij} + s_i + e_{ij} \qquad (6)$$

Respective prediction models for the parameters b and c of the Weibull distribution (Eqn 2) are as follows:

$$\ln(b_i) = p_0 + p_1 \times \ln(mode_i) + p_2 \times \ln(h_{\max_i}) + e_i \qquad (7)$$

$$c_i = p_0 \times (h_{\max_i} + 1)^{p_1} + e_i \qquad (8)$$

where $mode_i$ is the mode class of height distribution (m), $h_{\max_i}$ is the observed maximum height (m), and e_i is the random error term ($e_i \sim N(0, \sigma_e^2)$). Since the linearisation of a candidate equation for parameter c, which was multiplicative including an error term, did not improve the model fit, a nonlinear Equation 8 with an additive error term was selected. The least-squares estimates of the parameters of Equation 8 were obtained with an iterative Levenberg-Marquardt algorithm of SPSS software (1999).

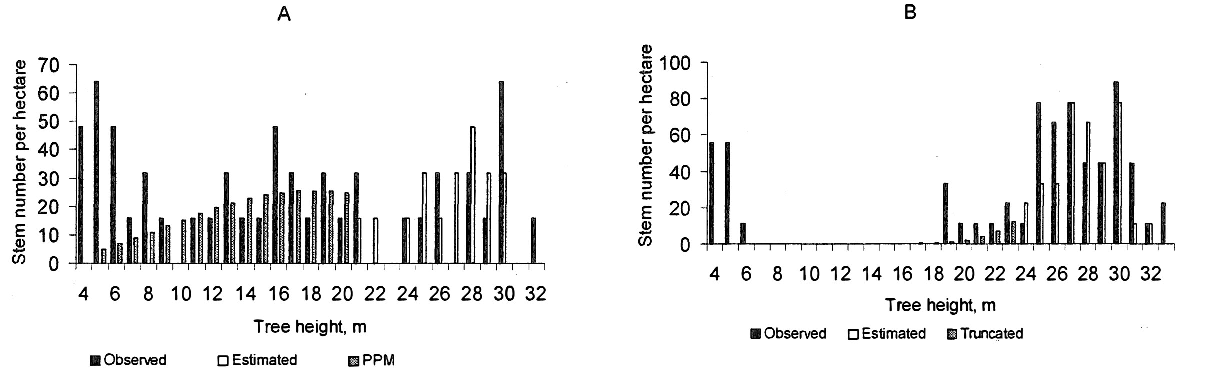

Fig. 3 Examples of the height distributions measured in the field (Observed) and detected by laser scanning (Estimated) combined with trees obtained from a theoretical distribution function Using (A) the parameter prediction method (PPM) and (B) a left-truncated distribution (Truncated).

Examples of the height distributions obtained with the parameter prediction method and the truncated distribution method are presented in Figs 3a and 3b. The fit between the original height distribution of field measurements and the estimate of laser scanning, both with and without the parameter prediction method (Fig. 3a), seems to be quite accurate. In the case of a left-truncated distribution the shortest trees cannot be described properly (Fig. 3b).

The RMSE of the original laser scanning was 25.0 % for plot volume and 74.4 % for number of stems, whereas biases were 24.3 and 61.4 %, respectively. When the parameter prediction method was used to describe short trees the reliability figures were in the case of RMSE 16.0 and 49.2 % and in the case of bias 8.2 and 6.3 %, respectively. With the left-truncated distribution approach the improvement in the accuracy was modest, the RMSE figures being 22.5 and 72.7 % and biases 21.6 and 59.2 %, respectively. Finally, the standard error of the volume estimates was

5.8 % for the original laser scanning, 14.7 % for the parameter prediction method and 6.3 % for the truncated distribution approach.

DISCUSSION

The accuracy prediction of plot volume of original laser scanning was already on a satisfactory level, the RMSE being under 30 %. Corresponding reliability figures for a laser scanning-based estimate of stand volume in boreal conditions have been reported by Persson et al. (2002) and Holmgren et al. (2003), for example. Holmgren et al. (2003) also found that the prediction of volume was slightly more accurate when using plot level models (22 %) than when using tree level models (26 %). In the present study, contrary to the good results in the prediction of plot volume, the RMSE of number of stems was very high, being over 70 %. The large difference between these figures is due to the fact that, according to Vuokila (1980), in boreal forests 85 % of the volume of the tree stock consists of the dominant tree layer. The obtained reliability figure for plot volume is comparable to the conventional field inventory by compartments. For example, in the study by Anttila (2002a) the corresponding figure was 32 %, although considerably more accurate results have also been obtained in studies on the checking of field inventories (e.g. Poso 1983, Laasasenaho and Päivinen 1986, Pussinen 1992, Ståhl 1992).

The level of accuracy is also dependent on the field material. In this study the size of the material was very small and the results should be considered regional or even local. In addition, the area has earlier been found to be heterogeneous in terms of the stand structure and species composition; it is difficult to interpret by using remote sensing methods and even to assess by means of stand variables (Hyyppä et al. 2000a). This is due to the high amount of tree stock and very dense understorey in some of the sample plots. Such stockings are rare in managed forest where the accuracy of laser scanning can be expected to be even better.

The standard error of plot volume of the original laser scanning was very low, being only 5.8 %. This figure is even smaller than in the study by Hyyppä and Inkinen (1999), where the accuracy was already better than 10 %. This indicates that laser scanning has the ability to produce highly accurate volume estimates. However, in both studies stand volume predictions are clear underestimates, the bias being over 20 %. Therefore, to be able to effectively utilise the laser scanning one has to solve the problem of how to calibrate the estimates. In this study the solution was to apply theoretical distributions to describe small trees using the approach originally presented by Maltamo et al. (2003). This methodology improved the results by means of both RMSE and bias, but, correspondingly, the standard errors increased somewhat. Comparing the application of this study to the original approach of Maltamo et al. (2003), the main difference is that the truncation point can now be freely chosen separately for each stand.

The approach using separate parameter models improved the results considerably, the RMSE of plot volume being only 16 %. This can be considered to be on the same level as a very accurate field inventory by compartments. The RMSE of number of stems also decreased considerably although the stem number characteristics were still slightly underestimated.

When applying the parameter prediction method one has to decide subjectively the truncation point for which the proportion of small trees is calculated by using a cumulative distribution function. Usually this point is selected just below the shortest detected tree although this may lead to unrealistically high estimates in some situations where only very high laser scanning-based trees are found. Another problem with this method is that the detected tree height distribution and the predicted distribution of small trees may not correspond to each other very well in all situations. All in all, this approach needs further methodological development and, especially, the selection of the truncation point needs to be studied more (see e.g. Vuori 2002). However, both larger field and remote sensing data are needed before it is possible to implement proper analyses on the subject.

The second alternative to describe small trees was to utilise the left-truncated form of the two-parameter Weibull distribution. Truncated diameter distributions have been previously considered for instance in the study by Zutter et al. (1986). The basic principle of this method is that the distribution function is estimated to the tree distribution observed from laser scanning. As in the case of the parameter prediction method, one has to choose the truncation point. This value is then used as the truncation parameter in the Weibull distribution, after which small trees are calculated by using information on the value of the cumulative function at the truncation point.

When applying the truncated distribution function the improvement in the results was only minor. The main reason for this is the fact that the shape of the height distribution resulting from the segmentation process is not truncated. Therefore, the cumulative proportion of small trees calculated by the Weibull distribution was usually very small, indicating that less than 10 % of the trees were not detected. This situation is not realistic since 60 % of the trees were not found with the identification method of single trees in the study area (Maltamo et al., forthcoming). In the case of the parameter prediction method the calculated cumulative proportions of small trees at the truncation point were considerably larger.

The methods used in this study to describe small trees are only capable of producing unimodal distributions. However, the study material included mixed forests also with multi-layered canopies. Therefore, it is possible that, although accurate results were obtained in this study, the description of the height structure may not be realistic, i.e. a given stand may include short and tall trees whereas tall and average trees were produced. For such multimodal stands a more complex methodology should be developed. If the height distribution is multimodal, then distribution approaches which can produce these forms could be utilised. Such methods include percentile-based methods, finite mixture distributions and non-parametric methods (Borders et al. 1987, Maltamo and Kangas 1998, Maltamo et al. 2000, Liu et al. 2002). In addition, it is possible to obtain at least some information on the occurrence of lower tree storeys by analysing the profiles of laser scanning data or percentiles of reflected laser pulse heights (e.g. Hyyppä et al. 2000b, Næsset and Økland 2002). It should also be remembered that the current crown segmentation method does not include recognition of tree species. If the detected single tree data were to include species information as well, the need for more complex methods in mixed stands would be minor.

Since the current segmentation method cannot separate trees growing close to each other, even if they belong to the dominant tree layer, it is obvious that the amount of detected large trees should also be calibrated. For instance, Maltamo et al. (forthcoming) found that only about 80 % of the trees of the dominant layer were recognised. Therefore, specific calibration coefficients could be estimated for each height class. Subsequently, small trees could be combined to estimates by using the more advanced methodology described earlier. This approach would be an effective calibrator of the obtained tree stock and the original very small standard error of the estimate would then remain low.

When applying laser scanning the saturation of forest reflectance is a minor problem. The plot volume of the most stocked sample plot was about 530 m^3ha^{-1} (measured in the field) and the estimate of laser scanning 440 m^3ha^{-1}. When small trees were combined to this estimate the total volume of the plot was 580 m^3ha^{-1}. When obtaining stand volumes of this magnitude it is more likely to have unrealistic estimates in boreal conditions. However, when these figures are compared to growth and yield series of managed and unmanaged stands (Ilvessalo 1920), it can be said that they still represent stands with the maximum yield potential. Therefore, when applying the methods of this study, the maximum level of possible stand volumes should be set.

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MEASURING INDIVIDUAL TREE CROWN DIAMETER WITH LIDAR AND ASSESSING ITS INFLUENCE ON ESTIMATING FOREST VOLUME AND BIOMASS

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ABSTRACT

The main objective of this study was to develop reliable processing and analysis techniques to facilitate the use of small-footprint lidar data for estimating tree crown diameter by measuring individual trees identifiable on the three-dimensional lidar surface. In addition, the study explored the importance of the lidar-derived crown diameter for estimating tree volume and biomass. The lidar data set was acquired over deciduous, coniferous, and mixed stands of varying age classes and settings typical of the southeastern United States. For identifying individual trees, lidar processing techniques used data fusion with multispectral optical data and local filtering with both square and circular windows of variable size. The crown diameter was calculated as the average of two values measured along two perpendicular directions from the location of each tree top, by fitting a fourth-degree polynomial on both profiles. The lidar-derived tree measurements were used with regression models and cross-validation to estimate plot level field-measured crown diameter. Linear regression was also used to compare plot level tree volume and biomass estimation with and without lidar-derived crown diameter measures from individual trees. Results for estimating crown diameter were similar for both pines and deciduous trees, with R2 values of 0.62-0.63 for the dominant trees (RMSE 1.36 to 1.41 m). Lidar measured crown diameter improved R2 values for volume and biomass estimation by up to 0.25 for both pines and deciduous plots (RMSE improved by up to 8 m^3/ha for volume and 7 Mg/ha for biomass). For the pine plots, average crown diameter alone explained 78% of the variance associated with biomass (RMSE 31.28 Mg/ha) and 83% of the variance for volume (RMSE 47.90 m^3/ha).

THE INFLUENCE OF THE FOREST TYPE ON THE DESIGN OF AN AUTONOMOUS SYSTEM FOR INDIVIDUAL TREE-BASED ANALYSIS OF LIDAR DATA

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ABSTRACT

The concept of individual tree-based analysis of lidar data is still in its early stages. To better interpret the results from the analysis more attention must be paid to the way forest type influences the lidar returns. To be able to automate the interpretation of real-world images, a technique similar to biological vision could be used. Scale-space theory is a framework for handling image structures (e.g. trees) at multiple scales that has been developed by the computer vision community. Trees of different crown sizes should be detected at different scale levels. However, the presence of sub-crowns that look like individual trees in some forest types complicates the decision process. Possibly, if the forest type can be estimated indirectly from the data, the computer system might be adapted to the new situation. Here the notion 'forest type' focuses on tree species composition and the width of the tree crown size distribution. To demonstrate the behaviour of different forest types in scale-space we introduce and discuss the difference between the optimal object scale and the optimal image scale. Certain differential geometry concepts can be used to analyse the canopy surface. We show how different forest types by necessity imply different strategies and illustrate our proposed adaptive analysis strategy with two different lidar data sets, both acquired with helicopter-borne SAAB TopEye laser profiling systems. The first data set was captured over a coniferous forest in southern Sweden 1998, and the second data set was captured during the winter 2001 over a senesced (leaf-off) deciduous forest in West Virginia, USA.

INTRODUCTION

Lidar data are useful for studying various forest properties such as timber volume, mean tree height and crown coverage (e.g. Nilsson, 1996). Most previous studies focus on the estimation of a locally averaged forest attribute per stand or sample plot (e.g. Næsset, 2002). The increasing sophistication of lidars, especially the expected higher rates of sampling frequencies (Flood, 2001), improves the economics of acquiring high-spatial resolution data. However, the technical development is not only limited to the lidars, but is also significant for other airborne sensors and satellite instruments. Consequently, a recent trend in the remote sensing research community has become detection and analysis of individual trees using various remotely sensed data, e.g. digital aerial photographs (e.g. Pinz et al., 1993; Gougeon, 1995; Pollock, 1996; Brandtberg and Walter, 1998; Hill and Leckie, 1999), lidar data (e.g. Hyyppä and Inkinen, 1999; Brandtberg, 2000; Næsset and Økland, 2002; Persson et al., 2002; Brandtberg et al., 2003; Warner et al., 2003) and high spatial resolution satellite imagery (e.g. Hui et al., 2000).

Several lidar-studies use various image processing approaches where scale-space theory plays a fundamental role in the detection process of visible and mostly overstory individual trees (e.g. Brandtberg, 1999, 2000; Ziegler et al., 2000; Brandtberg et al., 2001; Schardt et al., 2002; Persson et al., 2002; Brandtberg et al., 2003; and indirectly Hyyppä et al., 2001). Scale-space theory is a framework for visual operations originally developed by the computer vision community. Thus, an appropriately developed scale-space method is capable of handling the multi-scale nature of the image data from the forest under study. On the other hand, an inappropriately developed method could result in severe errors in the extracted forest information under certain conditions.

The entity 'forest type' has numerous meanings but here we focus on the local (approximately one hectare) structural complexity, indirectly induced by the tree crown size distribution and tree species composition. For example, in this study there is a clear difference between an even-aged, one-species plantation and an uneven-aged, naturally regenerated mixed-species forest. Different forest types, composed by individual trees of different crown size and species composition, behave differently in scale-space. This means that a method developed on one forest type might fail on another forest type, especially if the latter one is the more complex and challenging one.

There is also a possibility that a particular method appears as more successful than it is, just because the difficult forest types were intentionally or unintentionally avoided. Therefore this study draws the attention to the problem of different forest types and how they behave in scale-space and how differences between forest types could be discovered using various methods. The objectives of this study are to compare two significantly different forest types from two countries (Sweden and the USA), analyse their different behaviours in scale-space, and indicate which operators might be useful for forest type and / or species classification.

MATERIAL

For this study two different small foot-print high sampling density lidar data sets were available, both acquired with the TopEye instrument (Saab Survey Systems AB, 1997). The first data set (denoted A in this paper) was acquired in southern Sweden in 1998 (September 3-4) over mostly even-aged homogenous coniferous forest stands and the second data set (denoted B) was acquired in 2001 (February 1) over a mature senesced (leaf-off) deciduous forest in West Virginia, USA. For this study a one-hectare study area of data set A depicts an even-aged stand with Norway spruce (Picea abies) as the only species and the tree crown size distribution is narrow. From data set B a one-hectare area depicts a mixed forest type dominated by three canopy species: native oaks (Quercus spp; 48%), red maple (Acer rubrum; 16%) and yellow poplar (Liriodendron tuliperifera; 19%). This area has a relatively broad tree crown size distribution. More details about the two test sites and the two data sets can be found in Brandtberg (2000) and Brandtberg et al. (2003), respectively. Fig. 1 shows interpolated lidar data from the two different test sites. The numbers of visible trees are about 73 in the left image and about 60-70 in the right image.

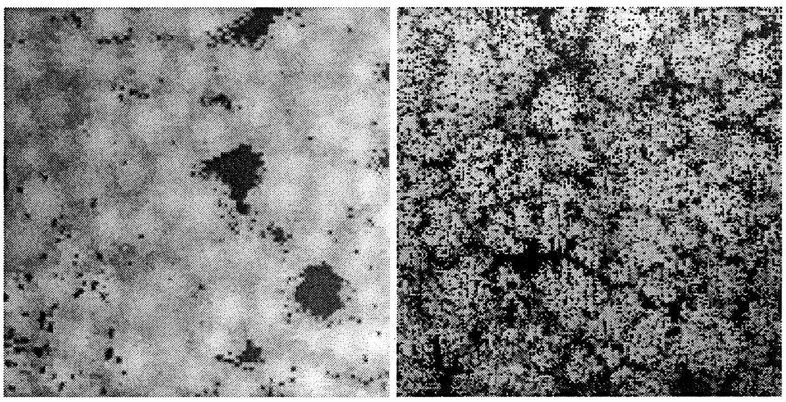

Figure 1: Left image shows interpolated lidar-data of a 50 x 50 m sub-area acquired over a Norway spruce stand in southern Sweden (data set A). Right image shows a corresponding image from a leaf-off deciduous forest in West Virginia, USA (data set B). Pixel sizes are 25 cm.

METHODS

This study is based on scale-space theory and differential geometry concepts in combination. A brief overview of the theoretical background is given below.

Scale-space theory, introduced by Witkin (1983), is a framework for visual operations developed by the computer vision community to handle the multi-scale nature of image data (a tutorial overview of scale-space theory is given in Lindeberg (1996)). An inherent property of these image structures (e.g. tree crowns) is that they only exist as meaningful entities over certain ranges of spatial scales.

A multi-scale representation of an image can be derived by convolution of the image with Gaussian kernels of different variances (scale parameter $t = \sigma^2$). The 2D Gaussian kernel at scale level t is given by Lindeberg (1993a):

$$g(x,y;t) = \frac{1}{2\pi t}\exp(-\frac{(x^2+y^2)}{2t}) \quad (1)$$

where *x* and *y* are the cell coordinates of the kernel centred at the origin (0,0).

An important issue when using scale-space theory is how to select appropriate scale levels for further analysis. One way is to make use of a scale-selection tool that is based on local extrema over scales of different combinations of normalised scale invariant derivatives ($\partial_\xi=\sqrt{t}\partial_x$) (Lindeberg, 1993a). At these scales distinctive structures can be detected and analysed further. It can be shown that an ideal Gaussian blob with characteristic radius $\sqrt{t_o}$ assumes a maximum of its scale-space signature at a scale (i.e., at scale t_o) proportional to the radius of the blob. The scale-space signature of a blob is given by the normalised Laplacian $|t\nabla^2 L| = t|L_{xx} + L_{yy}|$, where L_{xx} and L_{yy} are the second-order image derivatives along the x- and y-axes, respectively, computed at the spatial maximum of the blob. This or similar techniques were used on lidar data in Brandtberg et al. (2001, 2003) and probably also in Schardt et al. (2002).

Accordingly, for an image with numerous Gaussian blobs of the same size there is a single optimal scale level, based on the optimal object scale described above. This single level will be called the optimal image scale. If the blobs have slightly different sizes there is still such an optimal scale.

In this study we also make use of some fundamental concepts based on *differential geometry* (see Morse (2003) for a brief overview). Differential geometry is geometry using differential calculus, an approach that makes it possible to perform useful shape description and analysis of an individual tree or groups of trees in a forest. Scale-space approaches using these differential geometry entities can also be developed.

The lidar point data are initially interpolated so that the lidar height data are converted to a traditional digital image. The notation for this 2D image will be L(x,y), where (x, y) are the image coordinates. In this particular case we can think of 'L' as short for Lidar-image, but originally it stands for Luminance. The first and second-order image derivates are denoted L_x and L_{xx}, respectively. To be able to perform second-order geometry analysis the Hessian matrix (H) of second-order image derivatives must be defined. The eigenvalues and eigenvectors of H have important geometric meanings that will be used here. The first eigenvector is the direction of the greatest curvature and the second eigenvector (orthogonal) is thus the direction of the least curvature. The corresponding eigenvalues are the amounts of these curvatures. The concepts *principal directions* and *principal curvatures* are used in this context. The curvatures are denoted κ_1 and κ_2 and $|\kappa_1| \geq |\kappa_2|$ is thus always valid. In this study, the sum of the two principal curvatures is always negative on top of smooth convex tree crowns.

The principal curvatures can be used for various new concepts like Gaussian curvature, mean curvature, Laplacian and deviation from flatness. The Gaussian curvature K is the determinant of H and is $K = \kappa_1\kappa_2$. K indicates the local "extra" area a curved surface patch occupies as compared to a flat area. The mean curvature M is the average of κ_1 and κ_2 and it can also be found by calculating Laplacian = $L_{xx} + L_{yy}$ and dividing the sum by two. Another local surface measure is deviation from flatness (closely related to K) and is defined as $D = \kappa_1\kappa_1 + \kappa_2\kappa_2$. All these quantities are *invariant under rotation*, i.e. they do not change with arbitrary selection of spatial coordinate system (e.g. rotation). This latter feature is important because usually trees in a forest should be analysed irrespective of their spatial and rotational position.

Koenderink and van Doorn (1992) introduced a shape classification space, based on the principal curvatures described above, and this space is a Cartesian plane $\kappa_1 \times \kappa_2$. In this paper, we will use the polar form [S, C] of this space, which is defined in Morse (2003) as:

$$S = \arctan\left(\frac{\kappa_2}{\kappa_1}\right) \tag{2}$$

$$C = \sqrt{\kappa_1^2 + \kappa_2^2} \tag{3}$$

where S is the shape angle and C is the square-root of deviation from flatness D. Points with the same S (but different C) have the same type of shape according to this idea. For instance, when $\kappa_1 = \kappa_2$ the surface is spherical locally around the point under study. Because we are analysing convex surfaces only, the S-values will be normalised to percentage (%), instead of using radians. This means that 0% corresponds to an ideal conic-shaped object and 100% to an ideal parabolic-shaped object. Nelson (1997) concluded that the canopy shape affects lidar data and made use of several typical crown shape equations for simulation studies. Consequently, here we will estimate the canopy shapes (i.e. shapes of smoothed blobs in lidar-images) from our two different small-footprint high sampling density data sets.

The principal curvatures can be normalised in scale-space in the same way as the Laplacian, as described by Lindeberg (1993a). For instance, if the square root of the deviation from flatness (i.e. C) needs to be normalised, then C must be multiplied by the scale parameter t. A particular scale where the normalised operator response assumes a maximum for a blob[7] could be defined as the optimal scale for that blob. In this study, we analyse the operator responses at the spatial maxima of all blobs in the sub-image. In this way we can show how different forest types influence the characteristics of the response as a function of scale. Furthermore, the mean value within a sub-area in the forest (e.g. 50 × 50 m) could be defined as the optimal scale for the forest (a large group of visible individual trees). In Brandtberg (2000), a closely related method was defined to find a single optimal scale for each sub-image. Another approach is to analyse the whole convex and smooth canopy surface and calculate a mean value of the operator responses.

RESULTS

This section presents the results of the analyses of the sub-images in Fig. 1. The degree of Gaussian smoothing was selected as equal steps along the log(t)-axis. Fig. 2 shows the two test-images at scale t=20 (σ=4.5). The processing for Fig. 2 was carried out on an enlarged data set from that shown in Fig. 1, in order to avoid image edge effects. Both sub-images in Fig. 1 and 2, respectively, are on a slope; the left image is on a slope to the left and the right image is on a slope downwards. The tree heights are almost the same within each image and the ground is partly visible as relative dark areas. Note that laser beams that penetrated the upper canopy surface and reached the ground floor were <u>not</u> removed in this study.

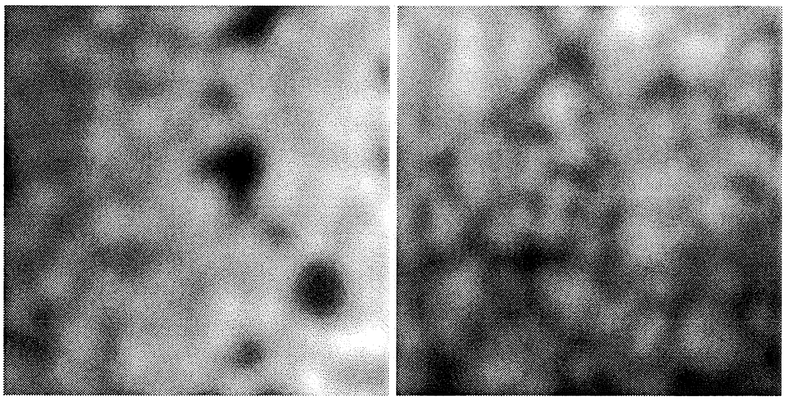

Figure 2: Left and right images show Gaussian smoothed (t=20) versions of the corresponding images in Fig. 1.

[7] A detailed mathematical definition of a bright or dark blob is given in Lindeberg (1993b).

The numbers of local maxima were counted in the two sub-images and their graphs as a function of log(t) are shown in Fig. 3. For both set A and B the graphs are continuously decreasing, but for set A there is a relatively stable scale interval where not much erosion of the objects take place. This means that the number of local maxima is largely unaffected by the smoothing process and thus few scale-space events (e.g. trees are merging with each other) take place.

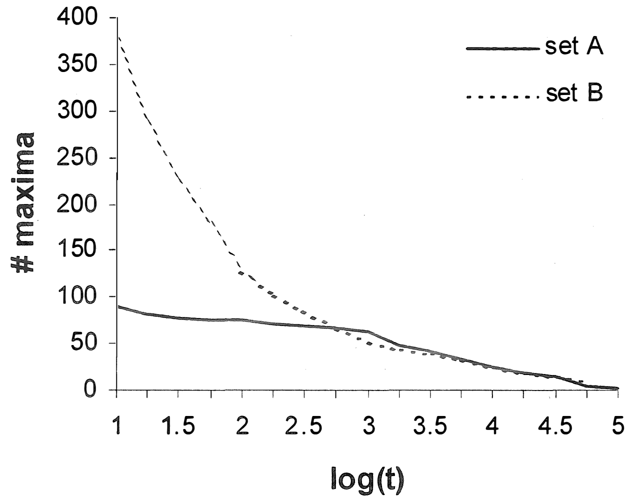

Figure 3: Plot of the numbers of local maxima as a function of log(t) for the two different sub-images in Fig. 1. Note the relatively stable plateau for data set A at log(t) ≈ 3.

Fig. 4 shows the mean blob signatures, computed at the local maxima, that were calculated according to the method described in Lindeberg (1993a). For set A the graph has only one reasonable choice of maximum. Conversely, for set B, the graph is relatively flat causing some ambiguity in the interpretation. However, there is a weak local maximum on the B-graph at log(t)=3.5 . These two scales are thus "optimal" according to this operator. However, this particular mean signature measure tends to overestimate the optimal image scale, but it is useful for other purposes (e.g. Brandtberg et al., 2003). The B-graph has greater magnitudes due to the higher image contrast caused by the visible ground between the trees, e.g. in Fig. 2.

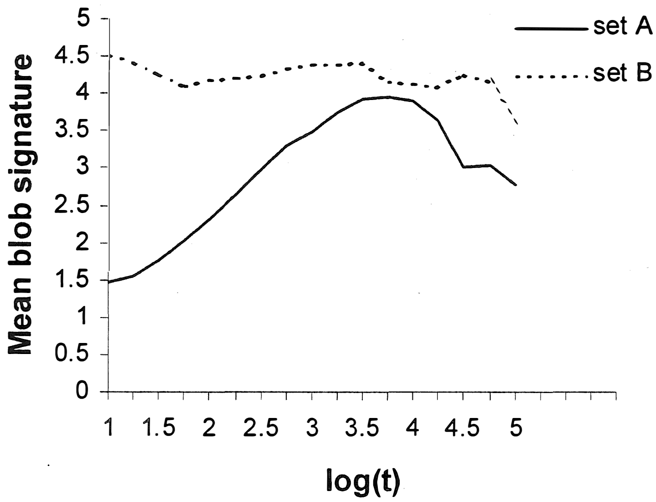

Figure 4: Plot of the mean blob signatures as a function of log(t) for the two sub-images in Fig. 1.

Fig. 5, which resembles Fig. 4, shows the scale-normalised mean square root of deviation from flatness as a function of log(t). The same conclusions are valid here as for Fig. 4.

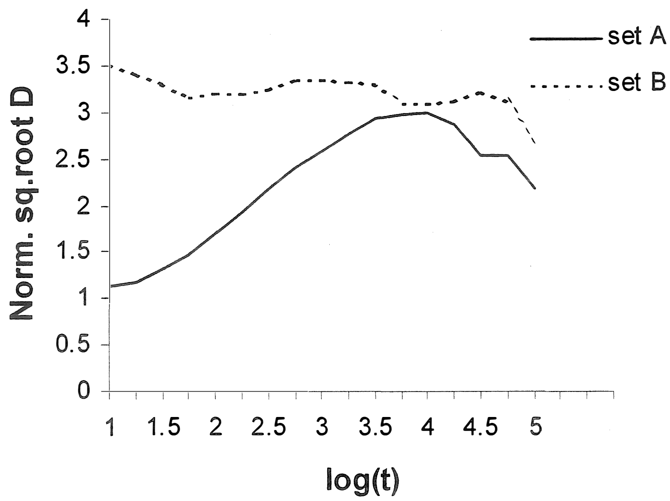

Figure 5: Plot of the scale-normalised mean square root of deviation from flatness as a function of log(t) for the two sub-images in Fig. 1.

Fig. 6 shows the mean shape angle for all local maxima within each sub-image as a function of log(t). The coniferous blobs are thus much more symmetrical than the deciduous blobs at the lower scale levels. When the coniferous trees are merging with each other they become more elongated, which is expected as long as they merge as two and two. The mergers of the deciduous trees are more random, which results in a relatively stable mean shape angle in scale-space.

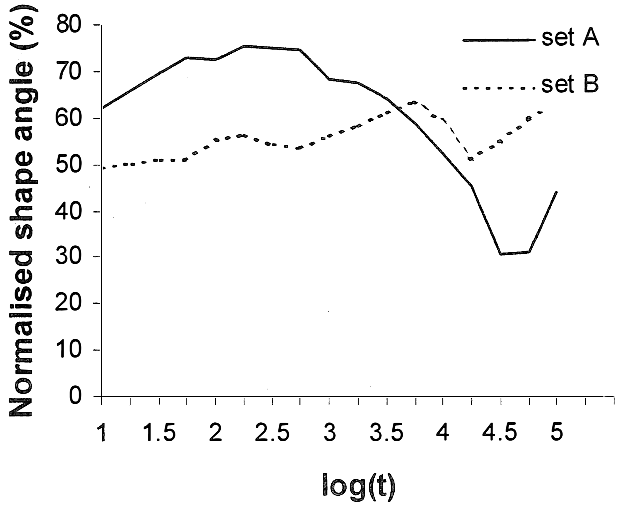

Figure 6: Plot of the normalised shape angle (in [0:100]) as a function of log(t) for the two sub-images in Fig. 1.

The standard deviation for the scale-normalised √D in set A (Fig. 5) is about 70% of the same value for set B (0.65 to 0.9) at t=20. This indicates, as expected, that the forest type in set A is much more uniform regarding the individual trees. The standard deviation for the normalised shape angle in Fig. 6 is approximately 20 for both sub-images over all scales. This indicates that the visible tree surfaces are changing their average shape continuously in the same direction under Gaussian smoothing, and thus follows the graphs slavishly.

Fig. 7 shows the graphs for the mean values of the shape angle distributions as a function of log(t) for the two sub-images in Fig. 1. If the 50%-level is treated as a delimiter between conic and parabolic-shaped objects it is concluded that the majority of the Norway spruce trees in Fig. 1 is more conic than parabolic, irrespective of the selected scale. Interestingly, the deciduous trees (set B) appear to be slightly more conic-shaped (i.e. < 50%) rather than spherical or parabolic-shaped at all scale levels (Fig. 7), which is quite the contrary of our expectations. Fig. 8 shows the result from a simulation study based on three typical crown-shapes (single blob images, radius 32 pixels), similar to the individual tree-based equations (as z=f(x,y)) given in Nelson (1997). Furthermore, a Gaussian-like blob gives a straight line at y=55% in Fig. 8. The graphs indicate how the theoretical crown models are affected by the Gaussian smoothing process.

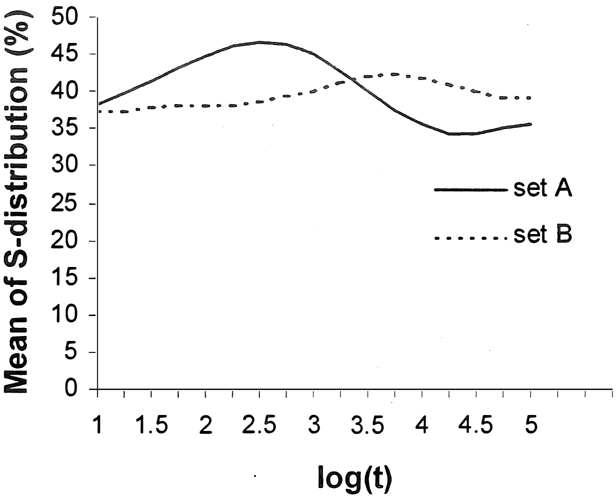

Figure 7: Plot of the mean value of the shape angle distribution (S) as a function of log(t) for the two sub-images in Fig. 1.

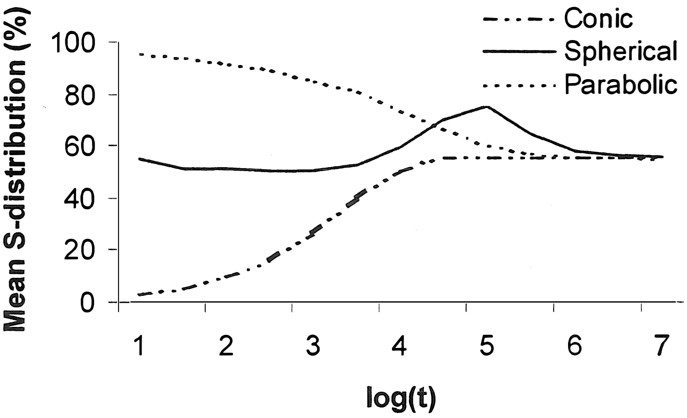

Figure 8: Plot of the mean value of the shape angle distribution (S) as a function of log(t) for three simulated typical tree crown shapes as z=f(x,y): conic, spherical, and parabolic, respectively.

DISCUSSION

In scale-space vision, the deciduous forest in this study is a generally more randomised-structured object as clearly shown in Fig. 3. There are no obvious single scale levels where all the trees are visible as single blobs and thus there are no inherent stable scale intervals in this forest type. Typically, the deciduous forest causes weak local maxima on some operator responses, if any. Laser beams that penetrated the upper canopy surface might be removed (e.g. Brandtberg, 1999, 2000; Persson et al., 2002; Brandtberg et al., 2003). However, removal or suppression of these beams does not affect the general shapes of the graphs in Figs. 3-7, even if the graph for data set B in Fig. 3 is significantly reduced in the beginning. The general shapes of the graphs are maintained, so it is concluded that the operation is redundant, especially when it is combined with scale-space (Brandtberg et al., 2003). However there might be another reason for the removal, e.g. creation of a manually interpretable image. Furthermore, the coniferous forest in Fig. 1 seems to be more opaque than the leaf-off forest. However, the B-data have higher sampling density (higher spatial resolution), which probably affects Fig. 1 and Fig. 3 to some extent.

In this paper it was shown that the forest type influences important operator responses directly. Complex forest types (as the B-data) characterised by several species and a wide range of crown sizes, behave differently in scale-space, making it harder to correctly identify individual trees. Unfortunately, it might be tempting to intentionally choose a simple forest type and claim that the new method is generally applicable. Therefore, an improved individual tree-based lidar-analysis system adapted to complex forest types, but applicable on simpler types, is under development and will be presented elsewhere.

CONCLUSIONS

Forest types influence certain operator responses in scale-space in different ways, so no generally applicable magic operator was found here. Simple forest types have often a single scale level where most of the trees appear as single bright blobs, whereas complex forest types have no such scale levels. In the latter forest type, a visible tree might never show up as a single bright blob at any scale. The general canopy shape (i.e. symmetry and type of shape) can be estimated from the smoothed lidar-image, but the numerical values depend on the degree of Gaussian smoothing. Differential geometry operators in combination with scale-space theory are powerful tools to analyse individual trees in digital images.

ACKNOWLEDGEMENTS

The Swedish National Space Board financially supported our attendance at the ScandLaser conference in Umeå 2003 under contract Dnr 186/03. The Swedish Council for Forestry and Agricultural Research (SJFR) financially supported the research projects 1995-2000 under contract nos. 20 .0040/95 and 20 .0755/97, and the group at TopEye AB in Gothenburg acquired the lidar data. The projects at West Virginia University received financial support from the National Science Foundation grant number DBI-9808312, NASA EPSCoR, and the West Virginia University Eberly College of Arts and Sciences. Aerotec LLC, Bessemer, Alabama, USA, is thanked for the leaf-off lidar data.

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DETECTION, MEASUREMENTS, AND SPECIES CLASSIFICATION OF INDIVIDUAL TREES FOR FOREST INVENTORY AND VISUALIZATION

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ABSTRACT

High-resolution airborne laser scanner data offer the possibility to detect, measure, and classify individual trees. Together with aerial imagery this data can also be used for 3D visualization of forest landscapes. An automatic method for detection, measurements, and species classification of individual trees is outlined here. First, individual trees are detected using a canopy model produced from laser data. Second, crown area and tree height are derived for each tree. Third, classification is performed based on features derived from laser data for each detected tree.

This method has been validated on twelve field plots (20×50 m^2) at the test area Remningstorp in southwestern Sweden. The field plots were dominated by Norway spruce (*Picea abies* L. Karst.) and Scots Pine (*Pinus Sylvestris* L.). In total, 71% of all trees with a stem diameter >0.05 m were detected. Since a large portion of the undetected trees had a small diameter, 91% of the total stem volume was detected. Height and crown diameter of the detected trees could be estimated with a Root Mean Square Error (RMSE) of 0.63 m and 0.61 m respectively. Stem diameter was estimated with an RMSE of 3.8 cm using laser measured tree height and crown diameter. Thus, most visible trees could be detected using laser data and tree height could be measured with the same accuracy as conventional field measurements of individual trees.

For classification of tree species, a classifier was trained with trees on all plots except for the trees on the plot that was classified. It was found that spruce could be separated from pine on an individual tree level with an overall accuracy of 95%. In ongoing work another classifier is under development to separate between pine, spruces and deciduous trees. Work has also been performed on combining laser data and aerial imagery to support the classification process.

Finally, we present some result on 3D visualization of forest. Laser data and aerial imagery are used in combination to build 3D models of forest landscapes.

INTRODUCTION

Laser scanner data offer the possibility to automatically extract information of single trees such as position, size and species. Using laser data a digital canopy model describing the outer contour of the tree crowns can be created. The canopy model is used to detect individual trees. Height and crown diameter of the detected trees can also be derived from laser data. Using the measured tree height and crown diameter, the stem diameter can be estimated and hence also the timber volume. Having delineated individual tree crowns, the tree species classification can be performed. The classification is based on the shape and structure of the tree crown as measured by the laser together with intensity data from the returned pulses.

An automatic method to detect and measure individual trees from laser data has been developed and validated at a test area in southwestern Sweden (Persson et al. 2002). Tree species classification of Scots pine and Norway spruce has been validated at the same test area (Holmgren & Persson 2003). Because the Swedish forest consist of 42% Norway spruce (Picea Abies L. Karst.), 39% Scots pine (Pinus sylvestris L.), and 19% deciduous trees (Anon 2002), classification into these three species classes would be very useful. Therefore further efforts are made to be able to classify the tree species into these three classes with high classification accuracy. Aerial images are integrated with laser data without any resampling of the image. One way to extract the star-shaped pattern that is typical for spruce trees from high resolution aerial images is demonstrated.

Research is performed at the Swedish Defence Research Agency (FOI) and the Swedish University of Agricultural Sciences (SLU) with the common aim to develop and validate methods for detection and measurements of individual trees. For several military applications, it is necessary to be able to efficiently create three-dimensional models of the environment. Using these models and, if available, aerial imagery, detailed and realistic 3D visualization models of the forest landscape can be constructed. There are many potential applications for visualization, e.g. landscape design, forest and territory management, and military and civil vehicle driving training. For forestry applications, forest variables need to be estimated for planning forestry activities. Areas of special ecological interest also need to be monitored, for example forest close to rivers or lakes. The possibility to detect and measure individual trees not only allow for detailed assessment of the present forest but also for applying growth models in order to visualize forest as it is expected to appear in the future. For example, a system for modelling individual tree growth is being developed with the aim to support ecological applications in multipurpose forestry planning (Söderberg & Nyström 2001). The starting point with this growth model project is that trees to a large extent dictate the conditions for other species. Trees are also manipulated by forestry treatments therefore regulating the ecological conditions. Data from permanent field plots from the Swedish national forest inventory is being used for building the growth models.

Current developments, both among system vendors and applied research, show a trend towards a combination of laser scanner data with digital images. High density laser data is useful for tree canopy delineation, and for measuring canopy shape and structure. Optical data is useful for classification of tree species by analyzing the structure of branches in the canopy. Another option is to integrate high resolution near-infrared images for separation of deciduous trees from coniferous trees. The aim of the ongoing work reported in this paper is to develop and validate methods for detecting, measuring and identifying species of individual trees using laser data and laser data combined with aerial images.

DATA COLLECTION

The data used in this work are from two different areas in southern Sweden, the Remningstorp forest estate (lat. 58°30'N, long. 13°40'E) and a military training area, Kvarn (lat. 58°40'N, long. 15°20'E). The data acquisition has been performed using the airborne laser scanning system TopEye which operates at a wavelength of 1.06 µm and with pulse rates up to 7 kHz. The measurements have an accuracy of 0.1 to 0.3 m (Sterner 1997). The forests of both areas are dominated by Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.) and birch (*Betula spp.*). At the Remningstorp estate, also field measurements of individual trees have been performed which has made it possible to evaluate the methods.

Remningstorp

The laser data acquisition was performed the 13th of September 2000. The area is essentially flat with a variation in elevation of 120 to 145 m above sea level. Laser measurements were made from five parallel flight lines in the north-south direction with a length of 2000-2500 m and a distance between the flight lines of 200 m. The flight speed was 16 m/s, the scan mirror frequency 16.67 Hz, and the scan width ±20°. The beam divergence was 1 milliradians and the flight altitude 130 m above ground giving a footprint diameter of 0.26 m on ground. The distance was 0.44 m between the laser-hits on ground within a scan line and 0.48 m between scan lines at nadir according to the flight specification.

Field measurements were made on twelve rectangular field plots (50×20 m^2) within the estate. Six of the plots were dominated (>80%) by Norway spruce and six by Scots pine. Within the plots, the position of all trees (≥0.05 m stem diameter at 1.3 m above ground), the stem diameters (1.3 m above ground), and the tree species were recorded. For a number of randomly selected sample trees (approximately 15 per field plot), the tree height and crown base height were measured using an ultra sound distance and angle device. The crown diameter was measured by projecting the outermost part of the crown to the ground and then measuring the distance on the ground in one direction as described by Jacobsons (1970).

Kvarn

At Kvarn, the laser data acquisition was performed over a 1500x2500 m^2 area in August 2000. The area was flown in two directions perpendicular to each other resulting in a final point density of about 15 points per m^2. The flight speed was 20 m/s, the scan mirror frequency 25 Hz, and the scan width ±10°. The beam divergence was 1 milliradians and the flight altitude 130 m above ground. High resolution aerial images were also captured over the area.

PRE-PROCESSING OF DATA

The algorithm for detection of individual trees works on gridded data (in this case 0.33x0.33 m^2) and two raster layers are therefore first created. One raster contains the highest laser point within each cell (DSM_{max}) and one contains the lowest value (DSM_{min}). In Figure 1b, DSM_{max} over an area in Kvarn is shown. A first step when extracting objects is to estimate the ground surface (*DTM*). The ground estimation works on DSM_{min} and is based on theories of active contours (e.g., Cohen, 1991; Cohen and Cohen, 1993; Kass et al., 1998). The contour can be seen as a net pushed upward from underneath the surface and attached to the laser points (Elmqvist 2002) (Figure 1c). When the ground level surface has been estimated, pixels above ground are further processed. Pixels more than 2 m above the ground level are classified as vegetation, buildings, power-lines, or posts by using local height variations and the shape of objects (Figure 1d). Also the ground pixels are classified as road or non-road pixels using the intensity of the returned pulses.

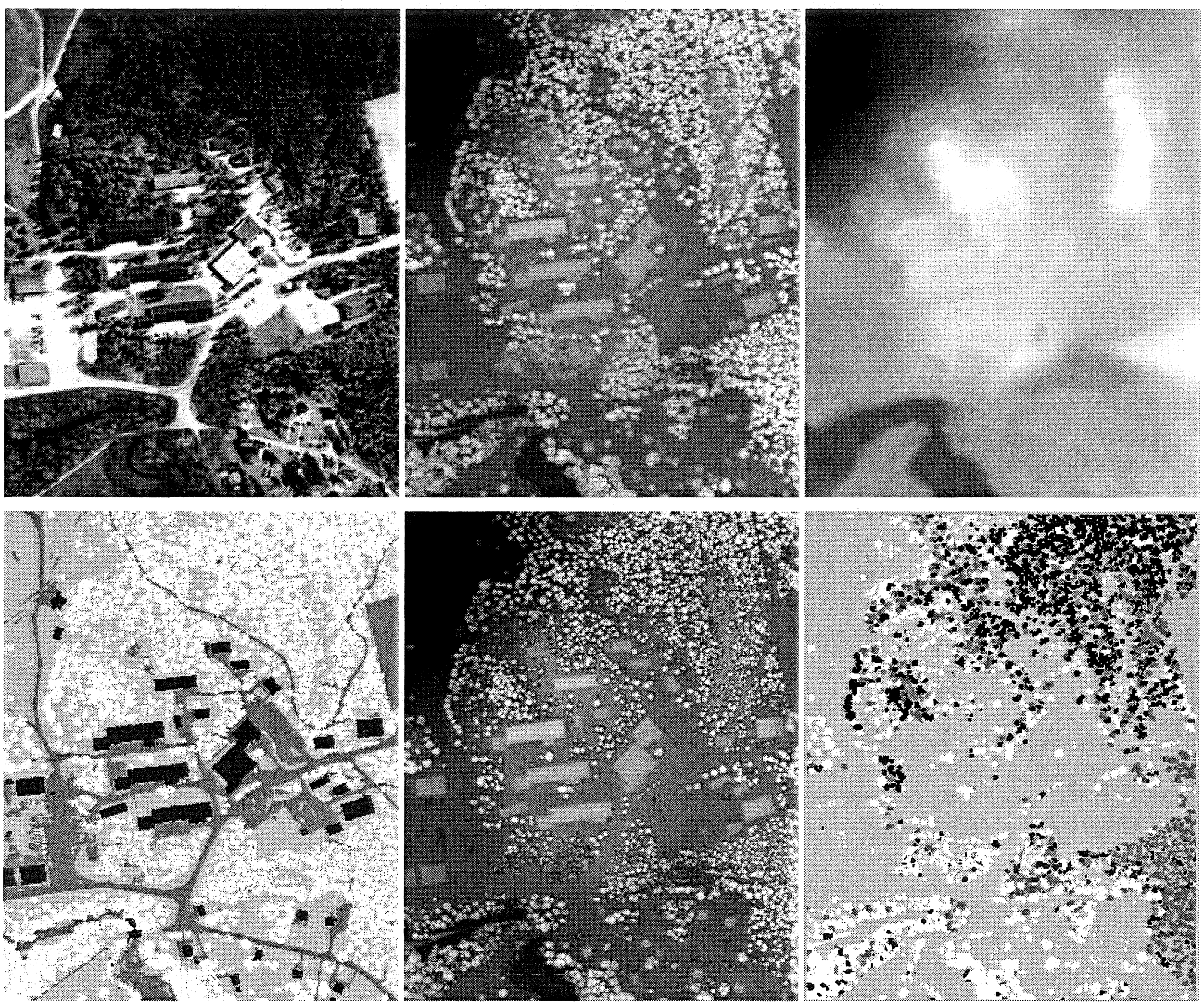

Figure 1: Extraction process. (a) Orthophoto. (b) Gridded height data (DSM_{max}). (c) Estimated ground surface (DTM). (d) Classification, ground (light gray), buildings (darkest gray), vegetation (white), power-lines (black), roads (dark gray). (e) Extracted single trees. (f) Tree species classification, spruce (black), pine (gray), deciduous (white).

ANALYSIS OF INDIVIDUAL TREES

Detection

The method of identifying individual trees consists of three main steps: 1) a digital canopy model (*DCM*) of the trees is created, 2) the *DCM* is smoothed with different scales and three different surfaces are produced and, 3) the appropriate scale in different parts of the image is determined (Persson et al. 2002).

Since the laser pulses often penetrate the canopy of trees with varying depth, there may be large height variations within individual tree crowns making it difficult to separate trees from each other. In order to exclude measurements that result from pulses having penetrated the canopy, the same active contour algorithm that is used to estimate the ground level is applied on DSM_{max}, but this time from above, in order to create the *DCM*. To remove height variations, left after penetration removal and caused by branches, smoothing is needed. The degree of smoothing needed so that each tree only has a single height maximum depends on the size of the tree crown. Since the tree size varies within a forest and is not known a priori, three different scales of smoothing are used. Finally, the appropriate scale in different parts of the image is determined by fitting a parabolic surface to the canopy model. Figure 1e shows the estimated crown coverage of the detected trees.

Measurements

For each identified tree, the tree position, tree height, and crown diameter are measured and stem diameter and timber volume estimated as follow:

Stem position - the centre of the pixel of a local maximum
Height - maximum height value above ground within a crown segment
Crown diameter - calculated using the area of a segment assuming the segments have the shape of a circle
Stem diameter - predicted using linear regression with height and crown diameter as variables
Stem volume - calculated using volume functions (Näslund 1947) with the height and stem diameter as inputs

Classification

After having detected single trees, the species of each tree can be classified (Holmgren & Persson 2003). All laser points within each segmented tree crown were grouped together to form the point cloud belonging to each tree. The laser points were divided into three groups according to their distances to the *DCM* or ground: ground hits, within crown hits, or *DCM* surface hits (Figure 2).

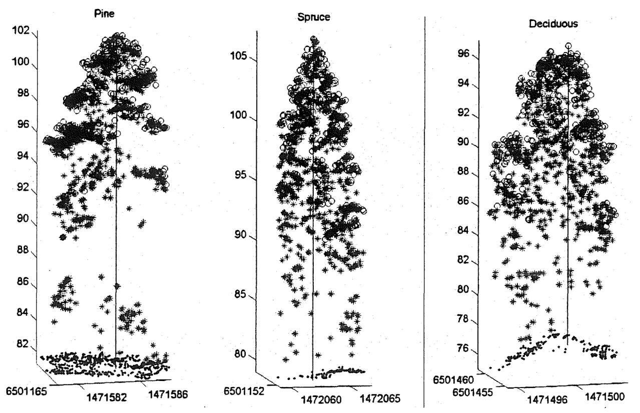

Figure 2: Laser points of a pine, spruce, and deciduous tree.

To separate between species, different variables are derived from the point clouds to capture differences in crown shape and structure. The extracted variables are based on proportion of laser returns of different types and measurements of height distribution, intensity, and geometry.

Variables with a high correlation coefficient ($|r| \geq 0.70$) between each other were grouped together. In order to test the difference in the two tree species group means, the student's t-test was performed for all variables and a t-value was calculated for each variable. Eight groups of variables were formed and the variable with the highest absolute t-value within each group was selected to be used in the classification.

The selected variables were:

Segp	*mean of a and b derived from parameters obtained from fitting a parabolic surface,* $z=a(x-x_0)^2+b(y-y_0)^2+c$*, to the laser points*
pveg -	proportion of returns that was located above crown base height
stdevint -	standard deviation of the intensity of the returned pulses
meansurface -	mean intensity of the surface returns
p2 -	proportion of first returns
psurface -	proportion of surface returns
relstdev -	relative standard deviation of laser heights
relperc90 -	the 90^{th} height percentile divided by estimated tree height

All variables were derived using only laser returns located above the crown base height. The crown base height was calculated using 0.5-m height layers. Each layer containing less than 1% of the total number of non-ground laser points within the segment was set to zero and the others to one. A one dimensional median filter (size 9) was then applied on the array of height layers to reduce the influence of laser points from low vegetation and neighbour trees. The crown base height was set as the distance from ground to the lowest laser data point in the first one-layer found.

The classification was performed using both classical linear and quadratic discriminant functions. The trees on one plot were classified using all trees on the other plots as training data. This was repeated until all trees on all plots had been classified.

Linking of laser detected and field measured trees for validation

Each detected tree in laser data was automatically linked to the corresponding field measured tree. For tree crown segments having only one field tree within the segment, the field tree was linked to the laser-detected tree. For cases when there were more than one field tree within the segment, the field tree that was closest (x, y-distance) to the position of the laser-detected tree was linked to the tree. Segments without any field tree were judged as false detections. Using this linking procedure that is only based on position could cause small undetected trees to be linked to large trees if positioned closer than the correct taller tree. Therefore, linked trees with a height difference of more than 1.5 times in height (seven trees) were excluded for the validation of measurements of individual trees.

RESULTS

The ability to link the trees made it possible to evaluate the results on an individual tree basis. Thus, it was possible to study number of detected tree, compare the automatically laser measured forest parameters with the manual field measurements, and evaluate the tree species classification results (Persson et al. 2002, Holmgren & Persson 2003).

Detection

In Figure 3a, the estimated and field measured tree positions are shown for one of the plots. This algorithm detected over 70% of the field measured trees, where most undetected tree are small (Figure 3b, Table 1). The detection rate for larger trees (stem diameter>0.20 m) is much higher, 90 %. Since most of the missed trees have a small stem diameter, 91% of the total stem volume is detected (Table 1).

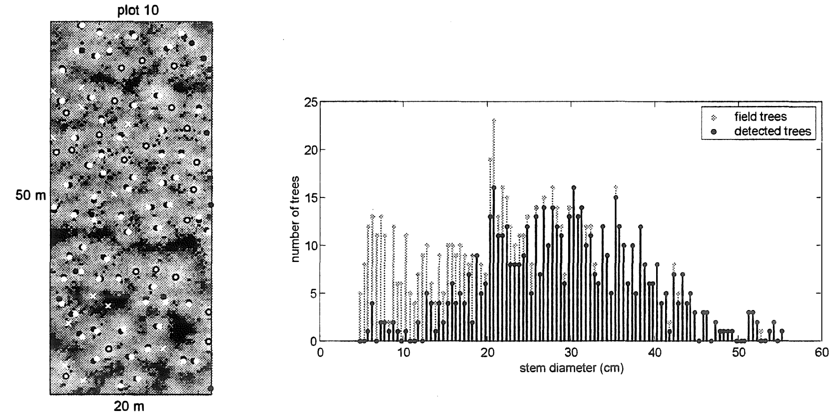

Figure 3: (a) Laser-measured position of treetops (black dots), field-measured stem positions (white dots), laser-measured and field measured position at the same pixel (black circle with a white dot in it), and undetected field-measured trees (white crosses). (b) Number of detected trees for different stem diameters.

Table 1: Number of detected trees and estimated stem volume on the field plots

Plot	Detected trees (%) with a stem diameter				Stem volume (m^3)		
	≥ 5.0 cm	>10.0 cm	>15.0 cm	>20.0 cm	Detected using laser data	Detected using field data	Total using field data
1	96	96	96	96	46	39	39
2	49	50	61	69	40	42	55
3	87	96	96	96	24	25	25
4	62	93	93	93	28	24	26
5	67	89	93	93	31	27	29
6	41	54	70	89	10	12	19
7	76	78	82	89	45	51	57
8	77	77	78	85	41	43	46
9	85	85	87	86	58	54	59
10	85	86	89	98	34	34	37
11	83	83	85	87	43	59	64
12	95	95	95	97	51	51	52
Total	562/795 (71%)	549/694 (79%)	531/621 (86%)	471/522 (90%)	451 (89%)	461 (91%)	508

Laser vs. field measurements

The field measured tree position, tree height, crown diameter, crown base height, stem diameter, and stem volume were compared with the laser estimates of these variables. The average positional difference of the stem positions was 0.51 m where the field measured position was measured at the center of the stem 1.3 m above ground and the laser measured position was taken as the position of the local maximum of the laser data (Figure 4a). Height, crown diameter, and crown base height of the detected trees can be estimated with a Root Mean Square Error (RMSE) of 0.63 m, 0.61 m and 2.82 m, respectively (Figure 4b-d). The correlation coefficient (r) was 0.99, 0.76 and 0.84, respectively. The crown base height was on average overestimated by 0.75 m.

The stem diameter can be estimated with a RMSE of 3.8 cm corresponding to 10% of the mean value (Figure 4e). Also, the stem volume of each sample tree, calculated using the laser estimated tree height and stem diameter, was plotted against the stem volume, calculated using the field measured tree height and stem diameter (Figure 4f). The RMSE of the volume estimates was 0.21 m^3 corresponding to 22% of the mean value.

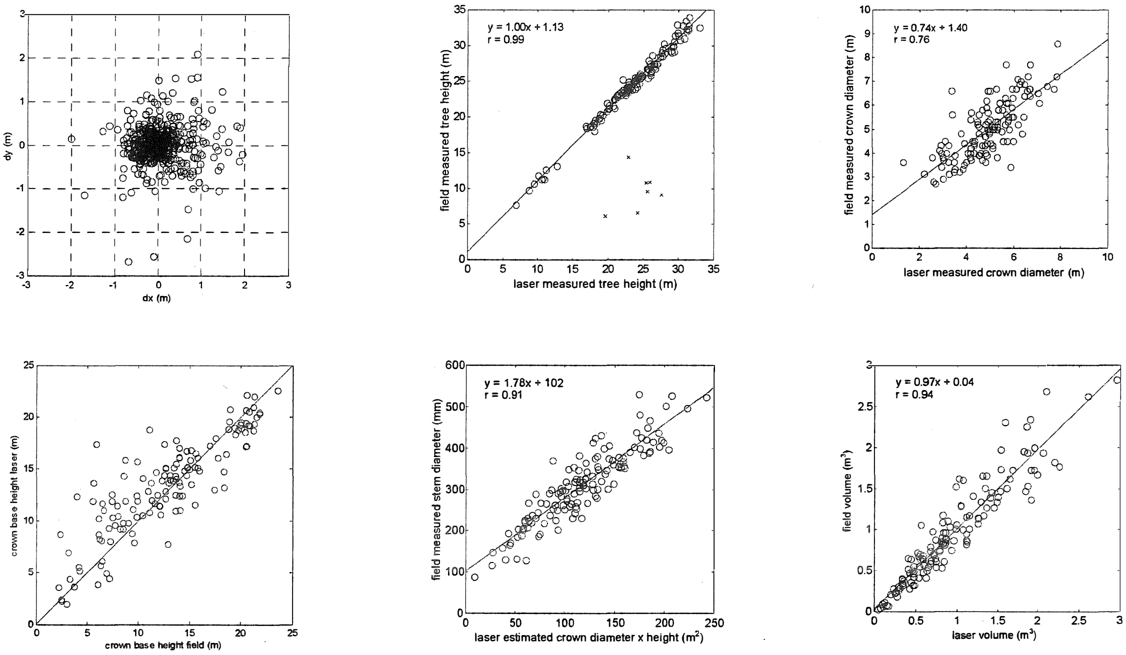

Figure 4: (a) Laser measured stem position, (b) tree height, (c) crown diameter, (d) crown base height, (e) tree height times crown diameter, and (f) stem volume of sample trees plotted against field measurements, 135 trees.

Classification

The classification was performed for all possible combinations of the eight selected variables. Table 2 shows the result for the best combination when using six variables. An overall accuracy of 95% was achieved.

Table 2: Classification results for both individual plots and for all plots together for the best combination when using six variables

Plot	Linear classification (%)	Quadratic classification (%)
1	89	85
2	78	78
3	93	93
4	95	95
5	98	95
6	100	96
7	100	100
8	100	97
9	92	88
10	99	99
11	89	95
12	95	93
total	95	94

VISUALIZATION

Visualization models usually consist of a ground surface model, a geospecific orthophoto or a geotypical ground texture map draped over the surface model, and a number of individual 3D object models placed on top of the ground surface at appropriate positions. The results from the tree analysis described previously form a very good input data set for 3D modelling of the forest landscape. The *DTM* can be used directly as ground surface model. The result of the tree species classification and the measured tree variables can be used to control construction of individual tree object models which are placed on the ground surface at the estimated positions. An orthophoto mosaic, constructed from aerial images, can be draped over the ground surface.

There are a number of different types of tree object models that can be used in modelling of the forest landscape. They are distinguished by their appearance and level of detail (Figure 5). If there are many trees in a forest, the level of detail of each individual tree will have a high impact on the complexity of the overall model. Therefore the most suitable tree model for an occasion depends on application requirements and the performance of the computer hardware for 3D visualization.

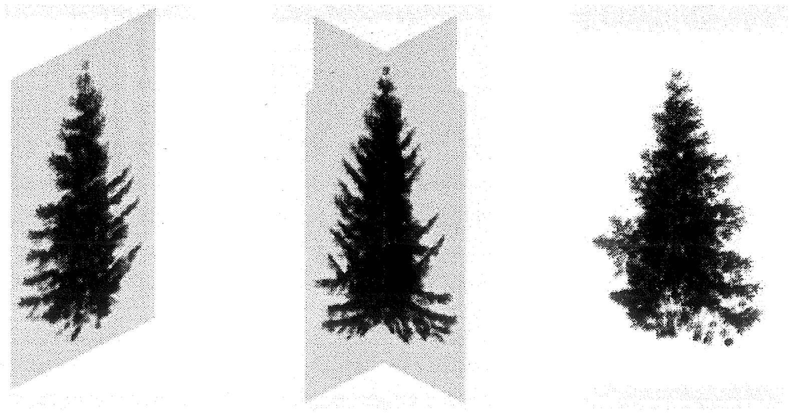

Figure 5: Three different types of tree models (Norway spruce) with different level of detail (number of polygons). (a) A "billboard" model where a picture of the tree is placed on a single rectangular polygonal surface, (b) a "crosshatch" model where two pictures are placed on two crossed rectangular polygonal surfaces, and (c) a full 3D-model constructed using a large amount of small planar polygon surfaces (in this case 138740 polygons).

Based on the data from the Kvarn area, a number of different models, different sub areas, different level of details, etc, have been constructed. In Figure 6, two different views from one model that uses billboard models for the trees are illustrated.

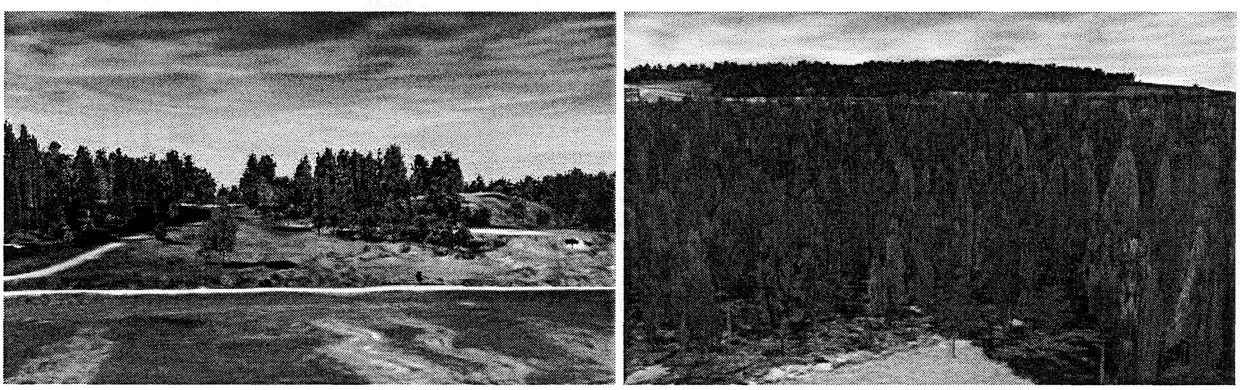

Figure 6: Two views from a model of the Kvarn area. Individual trees are modeled using billboard models.

ONGOING AND FUTHER WORK

Classification of not only pine and spruce but also deciduous trees will be performed and validated. Also, the available aerial images will be combined with laser data to support the classification.

Extended classification

At the Kvarn area, a classifier has been trained to separate between pine, spruces and deciduous trees. No field measurements are yet available for training. Instead trees of the different classes were selected from the aerial images by visual interpretation for training and validation. The result corresponds well with visual interpretation of the images (Figure 1f). Additional field measurements have been done in the end of 2002 at Remningstorp test area. The validation dataset now also include field plots dominated by deciduous trees. Laser data were also acquired over these additional field plots. Aerial near-infrared images were co-registered with the laser data.

Aerial images

Work has also been performed on combining laser data with aerial imagery to support the classification. The camera position (X_0, Y_0, Z_0) and orientation (*roll*, *pitch*, and *heading*) of each image can be obtained using the GPS- and INS-data from the laser scanning system.

Producing ortho-photos in forest areas will result in displacements of tree crowns if using the estimated ground surface (*DTM*) as height model. If instead the Digital Surface Model (*DSM*) is used, the trees will be more correctly positioned but have some distortion due to height variation within tree crowns that can not be modeled. Another problem is that the resampling during the ortho-rectification will change the spatial pattern in the image and therefore make texture analysis more uncertain. In order to avoid these problems, each tree segment was mapped to the corresponding pixels in the aerial image. The coordinates (*X*, *Y*) for each pixel in the segment together with their height (*Z*) were used to find the corresponding coordinates (x_p, y_p) in the images

$$x_p - x_0 = -f\left[\frac{m_{11}(X_p - X_0) + m_{12}(Y_p - Y_0) + m_{13}(Z_p - Z_0)}{m_{31}(X_p - X_0) + m_{32}(Y_p - Y_0) + m_{33}(Z_p - Z_0)}\right] \quad (1)$$

$$y_p - y_0 = -f\left[\frac{m_{21}(X_p - X_0) + m_{22}(Y_p - Y_0) + m_{23}(Z_p - Z_0)}{m_{31}(X_p - X_0) + m_{32}(Y_p - Y_0) + m_{33}(Z_p - Z_0)}\right] \quad (2)$$

where *f* is the focal length and x_0, y_0 the principal point. M is a 3x3 rotation matrix that contains trigonometric expressions of the rotation angles (*roll*, *pitch*, *heading*) (Boberg 2001). Since the images overlap, one tree can exist in several images. The image with its camera position (X_0, Y_0) closest to the center of the tree was used. In Figure 7, the corresponding segments in the images can be seen for some of the detected trees in the laser data set.

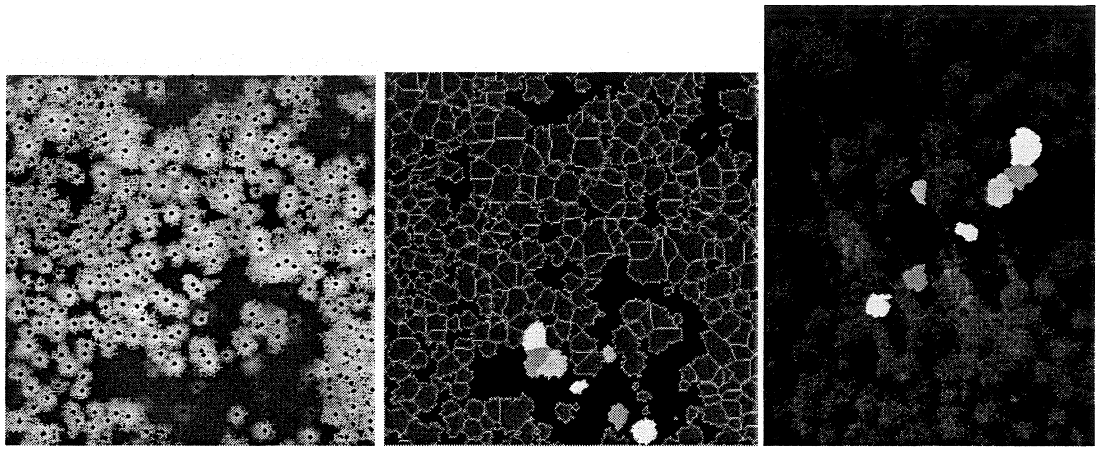

Figure 7: (a) Detected trees marked on the elevation data. (b) Estimated crown segments. (c) Corresponding crown segments in aerial image.

The delineated tree crowns from the optical images can be used to support the classification. Additional features based on spectral as well as spatial information can be extracted. The spectral information of near-infrared images could be used to separate between deciduous and conifer trees. A spatial image feature that can be extracted in order to separate spruce trees from other trees is star pattern of branches.

Initial attempts have been made to extract star-shaped patterns using the theory of rotational symmetries (Johansson 2001). Many different classes of patterns and symmetries can be described using the local orientation in double angle representation. In the double angle representation, a complex number, *z*, will have a phase that is double the local orientation, a phase θ will be represented with a vector pointing in the 2θ-direction ($z = e^{i2\theta}$). A double angle representation can be calculated using the image gradient $\nabla f = (f_x, f_y)$

$$z = |\nabla f|^{\gamma} e^{i2\arctan(f_y / f_x)} \quad (3)$$

where γ is a coefficient that controls the energy sensitivity.

A special case of rotational symmetries are *n*:th order symmetries, $\mathbf{z} = |\mathbf{z}|\, e^{i(n\varphi+\alpha)}$. Figure 8 shows examples of *n*:th order rotational symmetry patterns where each *n* represents a class of patterns and α class members. Different frequencies of the patterns can be used. The patterns are derived in [Johansson 2001]. In this example, the 2nd order patterns (circular, spiral, and star shaped symmetries) have been used.

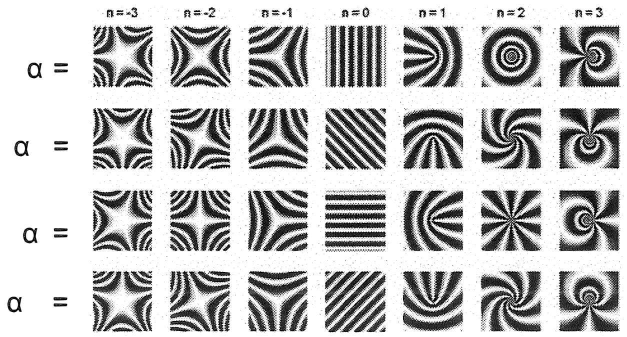

Figure 8: Examples of n:th order rotational symmetry patterns, $z = e^{i(n\varphi+\alpha)}$.

To detect features (e.g. star pattern), a local orientation image in the double angle representation is first calculated. Having defined the image in double angle representation, a rotational symmetry pattern can be detected by correlating $\mathbf{z}$ with a filter $\mathbf{b}_n = e^{in\varphi}$ which means that in each local neighbourhood the scalar product is computed

$$s_n = \langle \mathbf{a} \cdot \mathbf{b}_n, \mathbf{z} \rangle \tag{4}$$

where $\mathbf{a}$ is a window function (e.g. a Gaussian function).

An image pattern $\mathbf{z} = |\mathbf{z}|\, e^{i(n\varphi+\alpha)}$ will result in a filter output

$$s_n = \langle \mathbf{a}, |\mathbf{z}| \rangle\, e^{i\alpha} \tag{5}$$

A high magnitude $|s_n|$ indicates a high probability that the pattern belongs to class n and the agument $\angle s_n$ corresponds to the class member.

In Figure 9a, a crown segment of a spruce is shown. The image was represented in double angle representation and in Figure 9b the filter response is shown. The arguments of around 180° indicate that a star pattern is present.

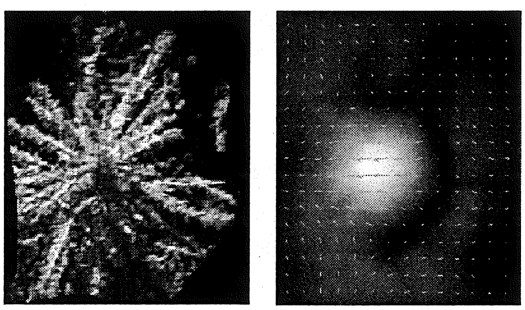

Figure 9: (a) Crown segment, spurce. (b) 2nd order rotational symmetry response.

Terrestrial laser scanning

In order to study the usability of terrestrial laser scanning for detailed forest mapping, a number of initial test have been performed. In these tests, the ILRIS 3D scanner from Optech Inc (www.optech.on.ca) was used. This scanner has a range accuracy of approximately 5 mm, a Field-of-View of 40°x 40°, and a spot spacing of <2,6 mm at 100 m. The maximum range is approximately 800 m (depends on material reflectivity).

The data sets produced by a terrestrial laser scanner can be viewed as range images or "point clouds" where each measured point have a (*X*, *Y*, *Z*) coordinate and an intensity values. The coordinate system is usually centred in the scanner itself. Using special software, different point clouds can be amalgamated using "common" points and coordinate transformations.

Figure 10: From left to right, two range images obtained using the ILRIS-3D terrestrial laser scanner, direct measurement of stem diameter in a range image.

In Figure 10, two range images obtained using the ILRIS 3D scanner are shown. Depending on what part(s) of the trees that are visible in the range image(s), a number of variables can be measured directly in the images, e.g. stem diameter, tree height and crown diameter. The position of the tree relative the scanner can also be determined directly, and if the scanner position is known in some reference system then the tree position in this reference system is also known.

The idea is to use this type of scanner to produce detailed maps of small areas in the forest, e.g., field plots used for evaluation and calibration of the data analysis methods for airborne laser scanners). This work is in its early faces.

CONCLUSIONS

The results show that it is possible to detect most of the visible trees, measure these trees, and identify the tree species of the trees using high density laser data. The accuracy of tree height measurements is similar to what can be expected by using traditional manual field methods (Lindgren 1984). It is possible to empirically relate laser measured tree height and crown diameter to stem diameter using a training dataset and in that way also estimate stem volume of individual trees. It is also possible to perform tree species classification using a local training dataset. The requirement of the training dataset, for example the geographical limitations should be investigated. Field methods should also be developed to efficiently obtain detailed training datasets that can be used together with the high accuracy airborne laser measurements. One option could be to use ground based laser scanners for retrieval of field data.

ACKNOWLEDGEMENTS

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ASSESSING PLOT-LEVEL FOREST METRICS WITH A GROUND-BASED SCANNING LIDAR

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ABSTRACT

A ground-based scanning LiDAR (Light Detection And Ranging) system was evaluated to assess its potential utility for plot-level forest mensuration data extraction. Ground-based LiDAR and field mensuration data were collected for two forest plots located within a red pine conifer plantation and a mixed deciduous stand dominated by sugar maples. Five LiDAR point cloud scans were collected from different vantage points for each plot over a six-hour period on July 5th 2002 using an Optech Inc. ILRIS 3D laser imager. Field validation data were collected manually over several days during the same time period. Parameters that were measured in the field, or derived from field measures included: (i) stem location; (ii) tree height; (iii) stem diameter at breast height (dbh); (iv) stem density; and (v) timber volume. These measures and plot estimates were then compared to those derived from the ILRIS-3D data (i.e., the LiDAR point cloud data).

It was found that all parameters could be measured or derived using the ground-based LiDAR system. There was a slight systematic under-estimation of mean tree height resulting from canopy shadow effects and sub-optimal scan sampling distribution. Timber volume estimates for both plots were within 7% of manually derived estimates. All parameters have the potential for objective measurement or derivation with little manual intervention. However, locating and counting trees in the multi-tiered deciduous plot required more subjective interpretation than in the pine plantation. Overall, ground-based LiDAR provide an objective and consistent methodology for forest metric assessment.

MODELLING OF VEGETATION STRUCTURE USING A LASER SYSTEM

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ABSTRACT

Three dimensional tree architecture determines light interception efficiency and is thus directly correlated to growth and photosynthesis efficiency. In the framework of an explorative study, the possibility to describe the structure of orchards by using a ground based laser-system was tested. The system consists of the SICK Laser Measurement System 200 (LMS200). The LMS200 is a compact non-contact optical measurement system which accurately determines the distance to the first object encountered along the path of the emitted laser beam. The laser scans the surrounding vegetation in a two dimensionsional polar plane by means of a rotating mirror (angular resolution of 0.25° and a frequency of 1550Hz). The third dimension was obtained by mounting the LMS200 on a moving platform that has a constant speed in the direction perpendicular to the polar plane. A field test was performed on twelve different orchard types and structural information was extracted out of the measured values.

The data were used to calculate the 1) 3D horizontal – and vertical distribution of vegetative material, 2) fractal dimension (FD) which describes the organisation of biomass in 2 dimensions after it is orthogonally projected onto a plane, 3) herbicide filtercapacity for spray efficiency, 4) shape and 5) volume of the orchards. Variables one, three and four differed significantly and were used to characterisize the different orchard types. Because of their incompatibility with traditional reference descriptors, a direct comparison was not possible. Variables two and five, on the other hand, were significantly correlated with reference data. Since the laser beams do not penetrate the canopy after the first reflection, detailed in depth description of the canopy was not possible. During the calculation of the LAI (parameter two), anomalies were encountered. These problems suggest that additional analysis is needed to optimize the laser-based measurement protocol.

The preliminary results show that the laser system offers a cost-efficient tool for describing the three dimensionel structure of complex vegetation canopies. In the near future, the laser system will be adapted to model natural forest canopies. An improved measurement protocol will provide three dimensional architectural information that will be analyzed using mathematical and visualisation software.

FOREST PARAMETER EXTRACTION USING TERRESTRIAL LASER SCANNING

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ABSTRACT

Quantitative forest measurements have traditionally been recorded using manual ground-based survey techniques. Whilst measurements such as tree diameter and height are relatively easily obtained using this method, it is more difficult to obtain accurate measurements of parameters such as tree taper without actually felling the tree. In addition, manual measurements are prone to some degree of measurement error. This study investigates the application of terrestrial laser scanning for providing quantitative forest parameters at the plot-level. The methodology was tested in Kielder forest, Northumbria, England using stands of mature Sitka spruce (Picea sitchensis) and of a Sitka spruce / Lodgepole pine (Pinus contorta) mixture. The stocking density between the two sites differed, with the Sitka spruce site thinned to approximately 600 trees per hectare, managed as a continuous cover crop. In contrast, the stand mixture although self thinning, had a density of 2,800 trees per hectare. The results of the study suggest that forest parameters such as tree diameter, taper and tree height can be measured directly from the laser scan point cloud return, in instances where the sensor's view of the tree is not obstructed. However, as shadowing caused by tree density or branching frequency increases, the amount of useful information contained in the scan decreases. Future work will look to assess the benefit of increasing the number of scans recorded in each plot in an effort to reduce this impact.

INTRODUCTION

In Britain, productive conifer woodlands cover approximately 1,658,000 hectares, this constitutes 60% of the total woodland area and 6.7% of the total land area of the country (Forestry Statistics, 2002). For the effective management and planning of this resource, an estimate of the volume of wood it contains is essential. At a broader scale such estimates can also be used to calculate forest biomass, from which carbon sequestration rates can be derived. Directly or indirectly, the estimate is based on the timber volumes of individual trees. Hence, estimation of stem volume is an important aspect of forest mensuration. Typically, this type of basic information is obtained using ground survey methods. Common measurement parameters at the compartment level[8] include mean top height[9], diameter at breast height[2] and basal area[10]. While these measurements are obtained easily using conventional ground-based sampling techniques, the benefit of laser scanning systems is that they able to acquire both basic and more detailed measures of timber quality characteristics such as stem form, which is dictated by tree taper (expressed in mm m^{-1}). Taper measurements are often made by felling or climbing the tree, which is time consuming and difficult. One of the obvious benefits of improved quantification of stem form is that it would lead to more accurate measurements of standing timber volume whilst also providing a non-destructive method of validating growth, yield and forest biomass models. Improvements of such models may lead to improved timber production forecasting and carbon stock estimation.

The aim of this study is to evaluate the potential of terrestrial laser scanning technology for providing accurate measures of forest parameters, and in particular measures of timber quality. The

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[8] *A compartment or stand is the primary management unit used in forestry. Typically compartments are homogeneous in terms of both tree species and growth.*

[9] *Mean top height is the average height of the 100 trees of the largest DBH (diameter at breast height, 1.3 m) per hectare.*

[10] *Basal area is the sum of all (living) trees in a stand, expressed in m^2 ha^{-1}.*

hope is that a method can be devised that automates the collection of such data that is both accurate and cost effective.

STUDY AREA

The forest areas used in this research are commercial upland conifer forest compartments located in Kielder Forest District, Northumbria, England (figure 1), and form part of a larger 55,000 hectare forest estate managed by the UK Forestry Commission. Field studies were conducted in two forest compartments. Site 1, located close to Kielder Water (latitude 55^{O} 12' N, longitude 02^{O} 35' W), is a mature Sitka spruce stand, planted at an initial density of 2,500 trees per hectare that had been progressively thinned over time to a tree density of 600 trees per hectare (figure 2). Site 2 is located 10 km south east of site 1 (latitude 55^{O} 07' N, longitude 02^{O} 28' W) and is a structured mixture of Sitka spruce and Lodgepole pine planted at 2,800 trees per hectare. Under this planting regime, a majority of the pine is either severely suppressed or in an advanced stage of decay (figure 3). At the time of measurement, the canopy was open at site 1 due to the recent thinning and closed at site 2. The understorey vegetation at both sites was a combination of dead needles and moss.

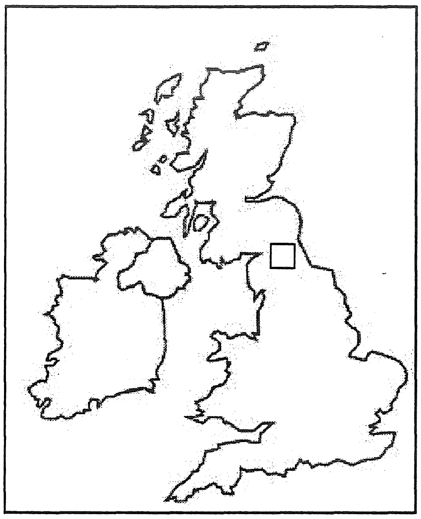

Figure 1. Location of the study area

Figure 2. Site 1, Sitka spruce stand

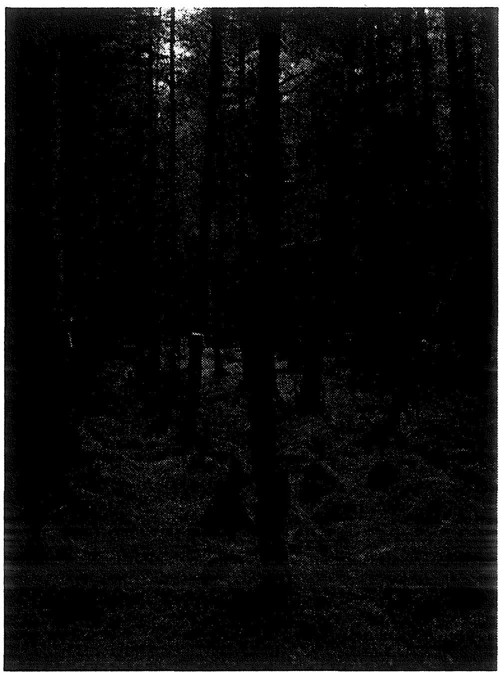

Figure 3. Site 2, Sitka spruce and Lodgepole pine species mixture.

DATA & METHODOLOGY

Two 0.02 hectare sample plots were established at each of the selected sites. The ground survey data recorded in each sample plot included measurements of tree diameter at breast height (DBH) and total tree height. The basal area was derived from tree diameter and sample size information. The summary plot statistics presented in table 1 shows that the main difference between the two sites is the number of trees per hectare, with site 1 having significantly fewer trees than site 2. The progressive thinning regime of site 1 has also resulted in an increase in mean diameter compared to site 2.

Table 1. Summary of measured forest parameters

Site Reference	Species	Planting year (Years)	Tree Density* (trees ha-1)	Mean diameter (cm)	Basal area (m2 ha-1)	Mean tree height (m)
Site 1	Sitka spruce	1933	600	34	60	26
Site 2	Sitka spruce / Lodgepole pine	1956	2,800	23	59	18.5

* Note: the tree density for site 2 is calculated for all trees, dead or alive. The figures for mean diameter, basal area and height are based on living trees only.

Three scans were recorded using a LPM-300VHS Riegl high-speed laser scanning system linked to a laptop computer (figure 4). This scanner has a vertical and horizontal scanning range of 150° and 180° respectively[11]. The scanning rate can be varied depending on the resolution required, with a maximum data capture rate of up to 12,000 points per second. The beam divergence increases by approximately 30 cm per 100 metres. The scanner emits laser pulses in the near-infrared range (~900 nm), with data captured as the scanning mirror oscillates continuously through the vertical and horizontal extent of the defined scanned area. Within this area, very accurate measurements of the objects distance from the scanner can be obtained by recording the time

[11] It is worth noting that that a key feature of this scanner is the ability to scan a hemispherical view (i.e. directly overhead).

taken for the laser pulse to hit the target and return to the sensor. The intensity of the return is recorded and quantized to 8-bits.

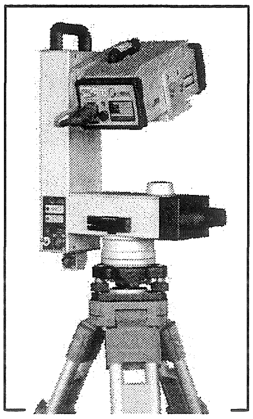

Figure 4. Riegl LPM-300VHS high-speed laser scanner.

Two scans of site 1 were recorded using two positions located diagonally across the sample plot to ensure adequate overlap of the scans. Reflective marker poles were located within the sample plot to provide reference points, enabling the opposing point clouds to be merged. Once merged it is possible to view and classify the forest structure in three dimensions using TerraScan ™ software (figures 6 & 7). The same method was replicated at site 2, although only one scan was recorded.

RESULTS & DISCUSSION

The results of the first set of intensity scans for the different sites are illustrated in figures 5 & 6. It is clear to see that the increased tree density and branching intensity of site 2 (Sitka spruce and Lodgepole pine species mixture) has a large impact on the effective range of the scan, which is approximately 8 m (i.e. equivalent to a 0.02 ha sample size). Despite this limitation it is possible to get an impression of the general structure of the forest and acquire measurements such as DBH for all trees. A measure of tree density can also be obtained by making use of the range information (figure 5). Furthermore, in some situations tree taper and branch frequency can be quantified up to the point where the lower canopy starts (4 m). Beyond this point, shadowing caused by dense branching prevents meaningful measurements being acquired.

Figure 5. Range image of species mixture, maximum range set to 8 m (note the backpack in bottom left corner of the scan).

In contrast, in site 1, (with 600 trees per hectare) the level of information that can be retrieved is improved with individual trees clearly resolved up to a distance of 30 metres from the scanner. For a number of trees in the plot a full profile from the base to the tip of the tree has been imaged. In these instances, total tree height can also be retrieved from the scan and tree taper can be calculated for the clear part of the tree bole. However, beyond this point the upper canopy obscures the scanners view of the tree stem.

Figure 6. Range image of Sitka spruce stand, maximum range set to 30 m.

By merging the two opposing laser scans a picture of the forest structure in three dimensions can be visualised and quantitative measures derived. Table 2, provides a comparison of field measured and laser derived DBH measurements for site 1. This data is also presented spatially in figure 7, with the red outline representing the laser return from the tree stem at a height of 1.3 m (i.e. DBH).

Table 2. Comparison of field measured versus scanner derived DBH for site 1

Tree No.	Field Measured DBH (cm)	Scanner DBH (cm)	Difference (cm)
1	34	34	0
2	44	44	0
3	29	28	-1
4	38	39	+1
5	34	34	0
6	29	30	+1
7	29	28	-1
8	42	44	+2
9	36	38	+2
10	43	39	-4
11	28	24	-4
12	29	27	-2

Overall the results presented in table 2 indicate that there are minor differences between scanner derived and field measurements of DBH. The largest difference is a 4 cm underestimation in the scanner derived DBH measurement for trees 10 and 11. In both cases the trunks of these trees were not clearly resolved either due to the acute angle of the scan (see inset) or where the scanners view of the target tree was obstructed by adjacent trees.

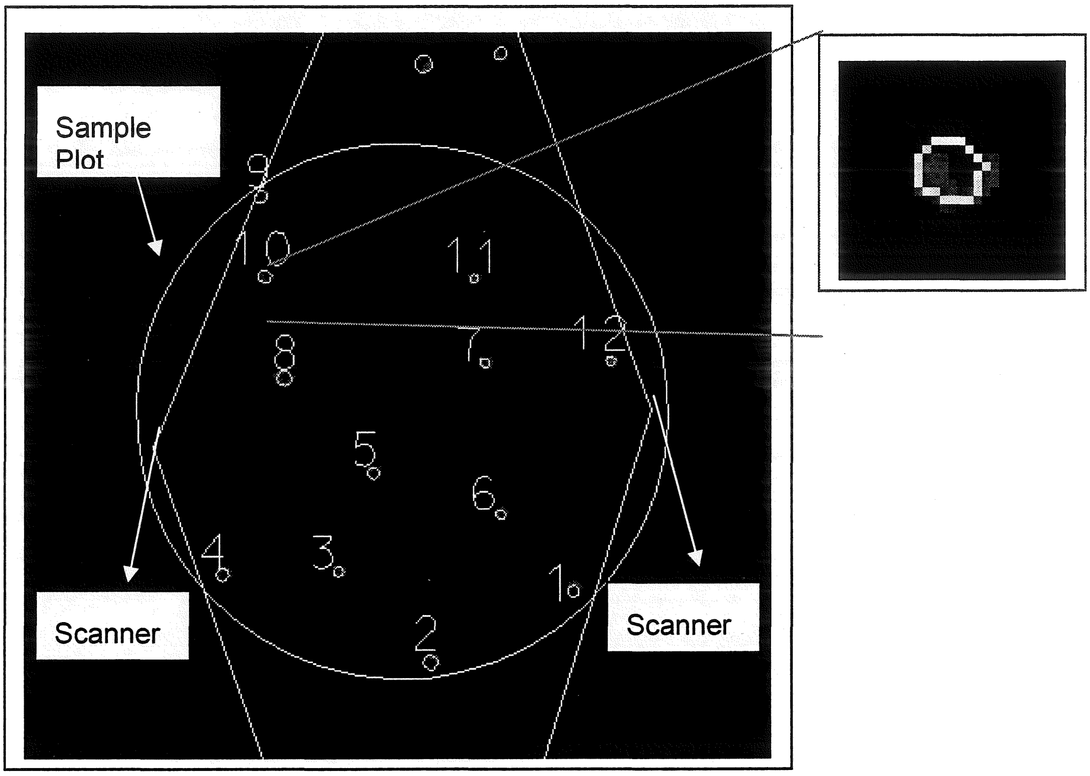

Figure 7. Plan view of site 1, with the opposing scans merged. Inset of tree 10 illustrates the effect of the scanner setting.

The main applications of this type of technology could well be the validation of existing forest growth models and quantification of above ground biomass. The results demonstrate that tree density has a significant influence on the level of information that can be retrieved from the laser data. The quality of the data retrieved in the lower density open forest stand is promising. In this environment it is possible to make accurate measurements of tree diameter, taper and in some cases total tree height. In denser stands (>2,500 trees per hectare) the quality of the information is significantly reduced. It is worth noting, however, that a majority of European boreal forests and Australasian plantation forests are more intensively managed, with stand densities usually ranging from 200 to 1,400 trees per hectare (Naesset, 2002; Watt et al., 2003). Perhaps a more prudent approach in densely stocked stands would be to scan smaller groups of trees, or even individual trees in order to improve the level of information obtained. Where wood volume can be calculated it should be possible to derive stand biomass and carbon content using published values of wood density and wood carbon conent. Figure 8, provides a plan view of site 1 classified into four vegetative categories; upper canopy (vegetation > 10 m from the ground), lower canopy (vegetation < 10 m from the ground), tree stems and the ground surface. This sort of information will be of interest to researchers modelling forest carbon sequestration rates as it is estimated for example that that the tree trunk generally accounts for 60% of the aboveground biomass (Imhoff, 1995).

Figure 8. Plan view of site 1, classified into four vegetative categories.

CONCLUSION

The results of this study suggest that it is possible to use terrestrial laser scanning data to accurately measure forest parameters such as tree diameter, taper and density at a plot-level. In situations where the scanner has an unobstructed view it is also possible to derive total tree height. However, as tree density and branching frequency increase, the usefulness of this type of information diminishes. In these situations single tree scans rather than wide angle scans may be a more appropriate approach. It is possible that laser scan data could be used for the calculation of standing timber volume, validation of growth and yield models and quantification of above-ground biomass. Future work will seek to evaluate the information content that can be obtained by high-resolution scanning of single trees. This may be an effective means of providing quantitative measurements of additional structural parameters such as canopy extent and volume and branch size and frequency.

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FINDING TREE-STEMS IN LASER RANGE IMAGES OF YOUNG MIXED STANDS TO PERFORM SELECTIVE CLEANING

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ABSTRACT

Cleaning and spacing in young forests gives remaining stems better growing conditions. The investment is considered high in Sweden, as the work is often laborious and there are difficulties in finding personnel for cleaning. New techniques, e.g. cleaning with autonomous artificial agents, e.g. robots, may be a solution but requires that stems are found automatically. The aim here is to test whether horizontal laser scanning can be used for finding trees in young forests. An automatic method for extracting tree stems in images created from laser measurements is presented. The user has to provide five situation-specific parameters. The proposed method is able to find the stems and measure the height and diameter on them.

INTRODUCTION

Forest management includes recurrent removal of trees during to whole rotation period. The purpose is to give remaining stems better growing conditions. When the main part of the cut volume originates from stems of less than 10 cm in diameter at breast height, the operation is called cleaning and spacing, or pre-commercial thinning, here denoted as cleaning (Pettersson & Bäcke 1998). This operation can be selective, geometrical, or a combination of both (Berg *et al.,* 1973). In the selective operation, the main-stems are chosen individually. A selected main-stem is a stem that is left, because it is considered to be of good quality or because it, for various reasons, is considered better than any nearby stems. In the Nordic countries, selective cleaning with a motor-manual brush-saw is predominant today.

The cleaning area, as well as the percentage of stems that are cut through cleaning, has been diminishing in Sweden; especially following the new revised Forestry Act of 1994, where it is no longer compulsory to perform cleaning (Vestlund 2001). Cleanings are today done at some 200,000 ha per year (Anon. 2002), but Pettersson & Bäcke (1998) states the yearly need to be about 300,000 ha. It seems thus, that the willingness to pay for cleanings is less than the actual costs. The work is also laborious and this might explain why there are difficulties in finding personnel for cleaning. Therefore, new techniques seem to be needed for making future cleaning less expensive and for reducing the human workload. Cleaning with autonomous artificial agents, e.g. robots, may be a solution. However, a crucial stage in making a selective cleaning system is the need to first automatically find and thereafter select stems in the stand. To capture information about the stand, machine vision could be used. Hague *et al.* (2000) describes this as a cheap, fast and powerful sensing method. Still, it has its drawbacks, especially in an out-door environment where it has to handle natural lighting conditions. Direct sunlight, shadows, and clouds will affect the collected data and artificial light will create shadows. Hague *et al.* (2000) states that other difficulties are storing and processing data, extracting useful information from the images, as well as dealing with natural objects.

Högström (1997) detected and segmented trees in a mature stand using measurements with laser, here the diameter of the trees were some 0.5 metres. Högström started by locating the trees to a 2-D histogram, thereafter labelled measurements within a vertical cylinder around the highest peaks in the histogram. To find straight but non-vertical trees he tried to find the centre line of the tree. Measurements belonging to two trees are removed. This process identifies and measure position as well as diameter for these relatively large trees.

The ability to find stems can also be used for "semi-automation" in cleanings and thinnings. Thinning is described as a mentally demanding work with complex decisions, precision work with crane and tool manoeuvrings, as well as high work-load. This can be a reason why many forest machine operators have neck and shoulder pains (Löfgren *et al.,* 1994). This mental stress was also found in mechanised cleaning (Gellerstedt 1997).

The aim here was to test laser scanning for finding stems in young forest stands with the intention of making a feasibility study of computer-based selective cleaning.

METHODS

In this study horizontal laser scanning was selected, since it does not depend on external light and since the captured information also includes distance data. The distance is interesting, because main-stems are selected both based on quality criteria and on relative positions.

Laser-measurements were made 26th of June in 2001, at Bennikebol approximately 5 km north of Arlanda Airport. The stand had 7,000 stems per hectare, 50% softwood and 50% hardwood. It was 15 years old and the average height was 4 metres. The laser scanning was made with an Accurange 4000 distance measuring laser mounted on a scanner developed by Mobile Robotics. The scanner was positioned at 0.6 meters above ground on a wooden box. Due to the uneven ground the box was slightly unstable which might have affected the measurements. The scanner has a theoretical maximum range at 20 metres and a distance accuracy of 1 mm. It is a modulated distance measuring laser with spot size of about 5mm in diameter. The scanning was made at 10 kHz, see Table 1.

Table 1: Information about the measurements.

Location	Picture size raw data (pixels)	Picture size processed data (pixels)	Mirror rotation angle (°)	Laser-plane angle (°)	Mirror rotation (Hz)	Estimated time (s)
Location 1	430*299	430*273	67,7-135	60,8-157,5	6,25	69
Location 2	589*400	568*361	45-135	45-177,6	6,25	94

The mirror rotation angle (α) determines how wide the scanning is and the laser-plane angle (β) the height of the picture. When the angle for both α and β is 90°, the scanning is made straight ahead. The number of measures was set to 400 per 90°; this determines the velocity of the mirror rotation. Each scanning produces five different layers of data for each pixel: the angles α and β, distance, amplitude, and ambience. Amplitude is light reflection and ambience is background light, Figure 1.

The raw data from the scanner was transformed into images. This transformation was made by a program supplied by Mobile Robotics. If rows or columns lacked many measurements they were removed from the transformation step. This is why the size of the processed data is smaller than the raw data. During the transformation step, trees in the outer part of the image also become slanted towards the centre of the image.

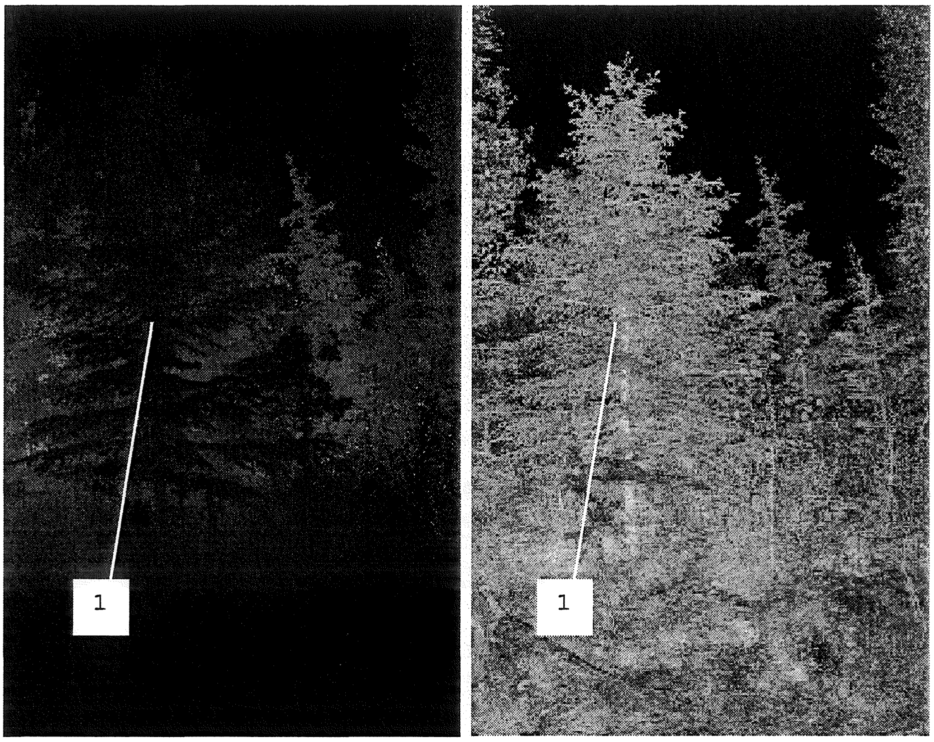

Figure 1: The left image visualise the distance values from the scanner. Dark pixels are near the scanner and bright pixels are further away. The pixels in the sky are dark because the distance from the scanner is too large to give any distance value. The right image shows the amplitude values for the same scene, the brighter the more reflectance. The images display tree no. 1 in Location 1.

Since we know that trees in the images have rectangular and more or less vertical stems we analysed the images to find vertical lines, i.e. trees. The method is automatic, but needs five user-defined parameters that can be situation dependent. Two parameters are the minimum and the maximum distance from the laser sensor. Two more are lower and upper values of the amplitude of the signal. The last parameter is a threshold, T, close to one, to decide if the found pixels can be considered to form a line segment or not. The following steps are used in the algorithm.

1. Find all pixels with the following properties:
    a. The distance value is inside its given interval.
    b. The amplitude value is inside its given interval
    c. The difference between the maximum and minimum distances in a region consisting of seven rows and one column around the central pixel is smaller than 0.15 m. Since the trees are locally straight, the region only has one column and some rows. Some distur bances in the laser measurements are present, and also the stems could lean towards or away from the sensor, therefore the distance 0.15 m is used.
2. Figure 2a illustrates the found pixels from this first step.
3. Check if the pixels found from step 1, in a given region, create line segments. Since the stems are vertical, but not straight, the size of the region used is 10 pixels wide and 30 pixels high. The check of straightness is done with Principal Component Analysis (Gonzalez & Woods 1993). Here the row and column value of the pixels are used as input to the PCA. The output is two eigenvalues representing the dispersion of the pixels in the direction of the respective eigenvector. If the ratio between the largest eigenvalue and the sum of the two eigenvalues is larger than the given threshold, T, it means that the pixels create a line segment. These pixels are kept for further analysis, Figure 2b.

4. A line is fitted to the pixels that are left, using linear regression analysis with the model y=Ax, where y contains the column values and A the row values. Outliers are removed with Jackknife residuals (Kleinbaum *et al.,* 1988) Figure 2c.

5. The last step is to include all pixels along the fitted line that fulfils distance and amplitude criteria. This is done by repeatedly taking one pixel from the ones included in the line and not yet investigated. By looking in a 3*3 neighbourhood of the pixel and adding all pixels fulfilling the criteria, the line is updated to include more pixels and a new pixel is taken for investigation, Figure 2d.

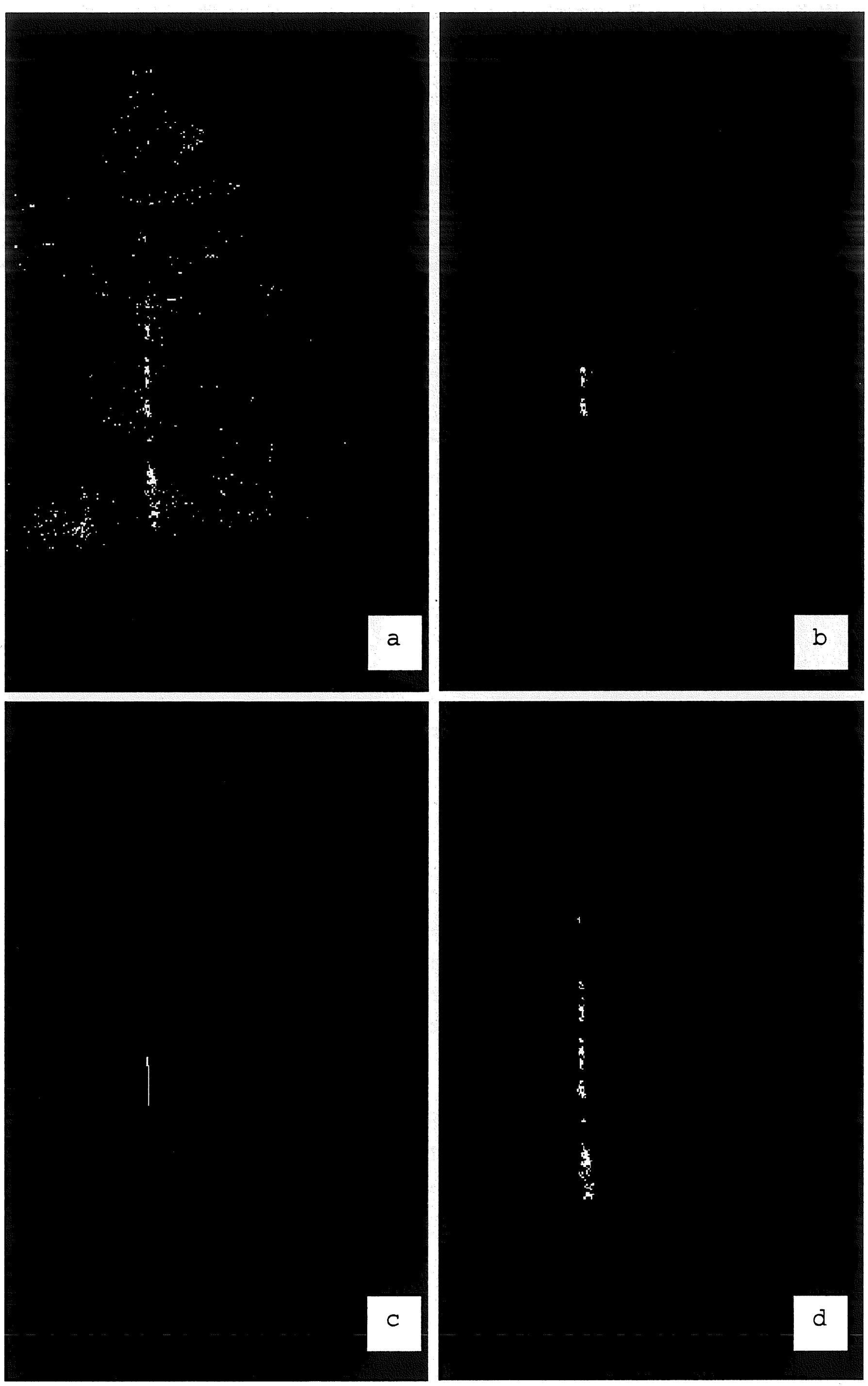

Figure 2: The method illustrated in images. (a) Pixels fulfilling the distance and amplitude criteria. (b) Pixels creating a line segment. (c) Outliers have been removed and a regression line has been fitted to the remaining pixels. (d) Extension of the pixels along the line that fulfils the distance and amplitude values.

From the final image, Figure 2d, it is possible to estimate the height and width of the tree, in which direction the tree is and the distance from the sensor to the tree. With the exception of the height, the estimation is done by subtracting the minimum value from the maximum value among the pixels in the last image. The height is estimated by subtracting the minimum height from the maximum height among the pixels in the resulting image from the first step, Figure 2a.

RESULTS

In Figure 3 results from the method are shown. The image corresponds to Figure 2d with the distance value image added for better viewing. All pixels belonging to the stem are not found, but this is not necessary in order to find the tree.

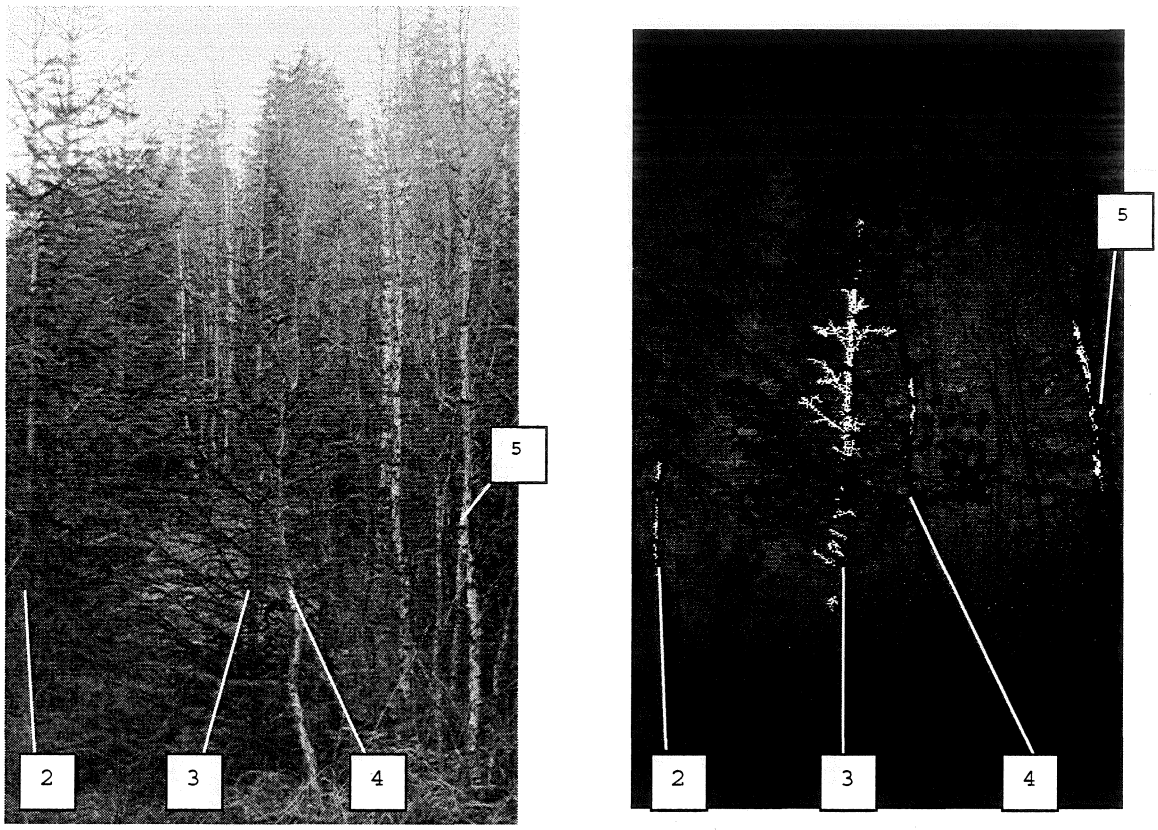

Figure 3: On the left a photo of the forest and on the right the laser image. The photo is taken from a higher point (1.5 m above ground) compared to the laser image (0.6 m above ground) which is the reason why the two images are slightly different. Tree no. 2 to 5 at Location 2 are marked. The pixels belonging to the found stems are shown in white.

Parameters estimated by the program and from field measurements are shown in Table 2 for the marked stems in Figure 1 and Figure 3. Distance measurements between the trees marked in Figure 3 are shown in Table 3.

Table 2: Tree data estimated by the program compared to manual measured data, in parenthesis. The manually measured diameter is taken at 1 metre above ground. The distance is from the scanner to the tree. O is the point where the laser scanning is made straight ahead, i.e. the angles α and β are 90°. All values are given in metres.

Tree no.	1	2	3	4	5
Diameter	0.05 (0.04)	0.03 (0.03)	0.5 (0.03)	0.02 (0.02)	0.04 (0.03)
Height	3.78 (3.8)	2.74 (3.9)	4.16 (3.1)	3.41 (3.2)	3.41 (3.9)
Depth	2.26	1.53	1.71	1.18	1.16
Horizontal deviation from O	-0.05	-1.33	-0.33	0.06	0.74
Distance	2.26 (2.3)	2.02 (2.1)	1.74 (2.0)	1.18 (1.5)	1.37 (1.7)

Table 3: The estimated distances between tree pairs for Location 2. All values are given in metres.

Tree pair	Distance
2,3	1.01
3,4	0.66
4,5	0.69
3,5	1.21

CONCLUSIONS

The proposed method is an automatic method which needs interaction with the user. One reason for not creating a fully automatic method without interaction from the user is the extra need of scans through the image and therefore also need for extra controls. At this early stage the aim was not to create a fully automatic method, but rather to see if the images are suitable for the task of finding stems for cleaning. This is also the reason for using pre-defined thresholds. If a fully automatic method is to be developed, some of the thresholds should probably be varying, or, even better, calculated from the image. One other thing that must be solved is the problem in step 2. It can happen that the found pixels are from different trees and then the regression line will be between the two trees instead of in one of the trees as in the usual case.

The method work fine when only the stems are to be found. However, the estimations of the parameters are not fully correct. The problem with the height is that the stems cannot be seen in the top of the trees. This is the reason for using the image from the first step when estimating the height. However, there are other stem characteristics that are more important than the height (Karlsson *et al.,* 1997). The diameter for tree no. 3 is incorrect due to the fact that we not only find the stem but also the branches.

The distance between two stems after a cleaning in stands 1 metre in height or more should be at least 1 metre (e.g. Brunberg 1990; Anon. 1999). This implies that either tree no. 4 or 5 should be cut (Table 3). According to today's cleaning instructions, preferably straight, vigorous, and undamaged stems should be selected to remain (e.g. Karlsson *et al.,* 1997). As seen in Figure 3, tree no. 4 has a crook and should therefore, according to these instructions, be cut.

More laser measurements are necessary in order to discover where, i.e., in which types of forests, this method can be used. Possibly more information on the adjustments will also be needed. Forest is a very heterogeneous and unstructured environment and it is not certain that a method that can find stems in one type of stand will be appropriate for another type of stand. With more measurements a more general conclusion can be made on how the stems could be extracted from the in-data. With more knowledge about the pros and cons of laser measuring, new ways to tackle the problem certainly will arise.

New measurements should contain other forest types, and perhaps also other sensor types. Bertozzi *et al.* (2000) states that millimetre-wave radars are more robust to fog and rain than laser beam sensors but are more expensive. This advantage might make millimetre-wave radar interesting to explore. Machine vision in combination with another sensor (e.g. laser scanner, radar) will probably be the solution to identify and position the target, i.e. the main-stem.

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AUTOMATIC DETERMINATION OF FOREST INVENTORY PARAMETERS USING TERRESTRIAL LASER SCANNING

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ABSTRACT

In the Natscan project terrestrial laser scanning is used for deriving detailed information about tree quality and forest stand parameters. The authors describe an automatic method for determining tree positions and diameters at breast height (DBH) using terrestrial laser scanner data. Special attention is given to the data-processing that must be carried out before this information can be derived from the raw data. First, a digital terrain model is calculated by creating a subset of coordinates containing lowest Z-values. Subsequently, filter methods are described to delete any noise points which result from the ambiguity problem connected with phase difference scanners. Finally, the process of tree stump coordinate and DBH determination by using Hough-transformation and circle approximation is described.

In comparison with a conventionally measured reference data set results for the stump coordinate and DBH are very promising. The differences fall within the expected range, although some improvement on developed algorithms is still necessary. The information derived so far can be used a basis for further automatic determination of other single tree characteristics such as tree species, tree height, crown projection area as well as location and type of wood defects.

INTRODUCTION

Information about current state and recent changes of forests are important basics for forest management and planning. In addition to well introduced airborne laser scanning, the use of terrestrial laser scanning is quite common in architectural measurements but has hardly been tested for the measurement of natural objects such as local terrain, standing trees or stags.

In the NATSCAN project one objective is to develop methods to automatically quantify characteristics used in conventional forest inventories. In addition, quality assessment of single trees in forest stands based on laser scanning techniques will be improved (Thies et al., 2002). The approach to the project is a combined inventory method which includes aerial laser scanners for covering large-scale areas and terrestrial laser scanners for deriving information about tree quality and inventory parameters as for example diameter at breast height (DBH), branch-free bole length, tapering or sweep of the bole based on sample plots. Terrestrial laser scanning, contrary to aerial laser scanning, measures trees from underneath the canopy and does this with very high resolution which is the basis for the described objective.

In this paper we roughly introduce the use of terrestrial laser scanners for forest inventories. Special emphasis will be placed on the automatic recognition of trees in point clouds representing sample plots with an average size of approximately 500 m². In addition to several filtering methods one pre-requisite for the automatic process is the separation of a digital terrain model (DTM) which is also described.

METHODS

The laser scanner

For our research we used the IMAGER 5003 from Zoller + Fröhlich which is based upon the spot Z+F Laser Measuring System LARA and can be fitted alternatively for two distance ranges, 25.2 m and 53.5 m.

Advantages of a phase difference scanner are both its high accuracy and its speed. The system realises an absolute accuracy within millimetre-range. As well as the distance, a value for reflectivity is also recorded. This intensity image delivers a 15 bit grey value image of the scanned area which is comparable to a black and white picture (Heinz, 2001).

The beam deflection unit enables one to image a 360° horizontal field of view and a 310° vertical field of view (the vertical view is cut off underneath the scanner). The maximum number of pixels vertically is 15,000, the maximum number of pixels horizontally is 36,000. The achieved angular accuracy for this deflection unit after calibration is approximately 0.01° (Zoller + Fröhlich, 2003).

A disadvantage of a phase difference scanner is the limitation of the maximum distance. When objects are beyond the ambiguity interval the results will contain additional point-noise. Measured distances in forests are usually greater than 25 metres, therefore we use a scanner with a range of 53.5 metres.

Measurement setup

The sample plots are scanned from various positions. On average, four scans evenly distributed around the centre of the plot were made, each about 10 to 15 meter distance from the centre of the plot, so that a central overlapping zone was guaranteed. Targets were used to match the data from the different scans and to orientate the point clouds in a georeferenced coordinate. These targets were placed in such a way so that they are visible in most of the scans. At least three targets were necessary to register a scan. To achieve higher accuracy we insured that between five and six targets were visible for each scan (figure 1). For georeferencing the point clouds targets were measured with a total station and connected to the German national coordinate system (GAUSS-KRUEGER coordinates).

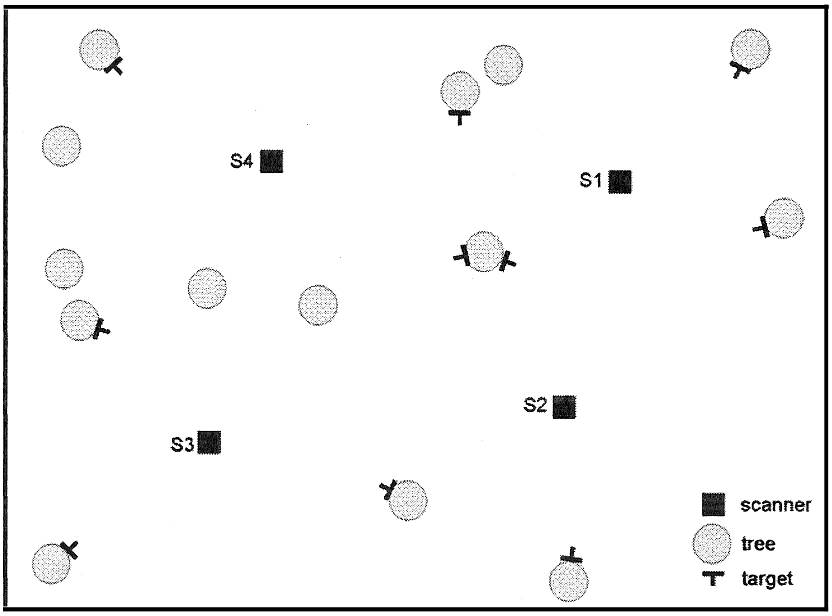

Figure 1: Typical measurement setup.

Digital Terrain Model

In a first assumption a good recognizable feature of a tree is a perfectly circular stem cross-section. For the selection of points representing stem cross-sections, a digital terrain model must first be determined. In later stages of data analysis these terrain models also help to derive tree heights and to calculate the slope and orientation of a stand.

A disadvantage of the laser scanning technique is that all measured points are unqualified. Points only represent their positions and intensity and not on which object they reflected. To select points which represent the ground surface the first step is to search for the lowest points. For this purpose the point cloud is separated in a grid with a regular size of 50 x 50 cm. In each grid cell the point with the lowest Z-value is selected. This sub-sampling of coordinates is the base point collection for further analysis. In the next step these data points have to be tested against an exclusion cone around the scanner and a-priory information about what the estimated maximum terrain height and the maximum steepness of a slope are. From the scanner position a cone is projected which describes the relation of surface height and distance to the scanner (figure 2). Coordinates inside this cone will be ignored.

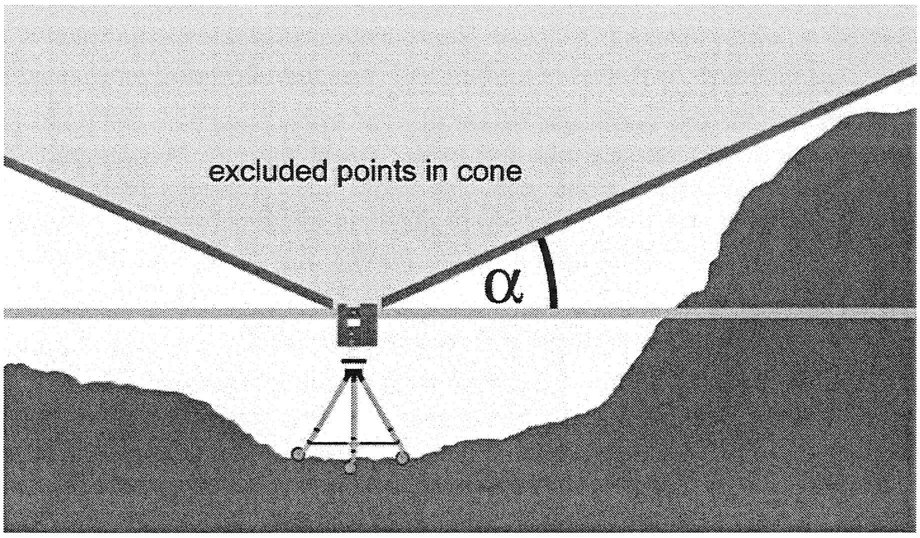

Figure 2: Exclusion cone. All reflected scanner points within the cone above the scanner will not be used for the determination of the ground surface. The dihedral angel of the cone is 180° - 2α.

Clearly a point representing a height above the maximum terrain height cannot be part of the ground surface, so if a point in the selection is much higher than its neighbouring points and exceeds a given maximum the point will be deleted. The last automatic test on the surface points is a maximum slope test. If a point causes a steep slope in the surface it will be removed.

An optical test is still essential after finishing the automatic derivation of the collection representing terrain coordinates. This test can be carried out on the drawn points. Points that are obviously not part of the surface can be manually removed from the selection.

A digital terrain model with a grid size of 50 x 50 cm is calculated with the selected points.

Filtering

Due to the ambiguity problem the resulting point cloud from a laser scan includes point noise. Points reflected at a 60 meter distance from the scanner behave as if they were only 6.5 metres away (60 meters minus the wave length of 53.5 meters). Before any algorithm can be applied to the data, these pixels must be identified and removed.

The first filter technique we use is a filter that deletes isolated points. Searching along the scan direction every single point has four neighbouring pixels. If the distance of a pixel is extremely different from its neighbouring pixels it is separated as isolated coordinate and deleted from the point cloud (figure 3b). The second filter used for noise detection is based on the intensity of the reflection. The intensity value of measured points ranges from 0 to 32,767. A very low value indicates a reflection from a point beyond the ambiguity range and can be considered to be point noise. According to our experience natural objects never have high intensity values. This means that a very high intensity (e.g. 20,000 or higher) also indicates point noise when measuring in forest stands. After using both filters most point noise is deleted from the dataset (figure 3c).

Figure 3a: Intensity Image of a scan; b: point cloud without isolated points, filter by a value of 2 metres; c: point cloud b filtered by points of an intensity less then 500 and more then 20,000.

Another disturbing factor for the automatic separation of trees based on 3D-point clouds are the foliage and branches between the scanner and trees. These have to be detected. To isolate tree boles from overlapping branches regions with only slight differences in distance values between neighbouring pixels are separated. The density of pixels is relatively high close to tree boles (corresponding to little distances between neighbouring pixels). If a chosen distance is exceeded pixels are not recognised.

Coordinates of tree stump base and diameter at breast height

Using the digital terrain model a search for circles as a model of tree cross-sections has been implemented. To find these circles all coordinates in a layer with a height between 1,25 and 1,35 metre above terrain were extracted from the point cloud. The 3D coordinates were converted to a regular raster image (figure 4). For this conversion a pixel size of 1 cm² was chosen.

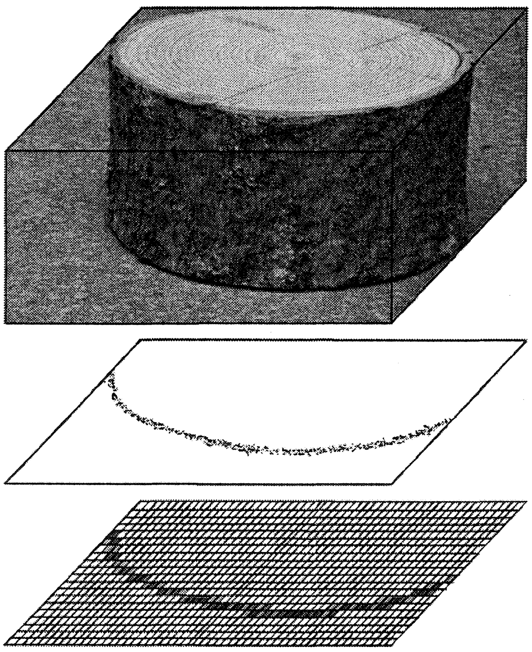

Figure 4: The selected layer of 10 cm height will be covered with scan points. These scan points will be mapped on a plane and fitted to an regular raster of 1x1 cm.

After this conversion is done, standard pattern recognition methods can be applied. We decided to use a Hough-transformation to detect circles in raster images.

The Hough-transformation uses a parametric description of simple geometrical shapes in order to reduce the computational complexity of their search in a binary edge image. The method for searching circles use the parametric description:

$$(x-a)^2 + (y-b)^2 = r^2 .$$

With a fix radius r the parameters a and b stretch a parameter matrix P(a,b). For every filled pixel (value 1) in the binary edge image a set of corresponding parameter values a and b is calculated matching the defined value r. The appropriate parameter matrix P(a,b) will be increased by 1 for these parameters. At the end of the procedure, each parameter matrix element P(a,b) shows the number of parameters that satisfy. If this number is above a certain threshold a circle is declared (Pitas, 2000 and Paulus et al., 2001).

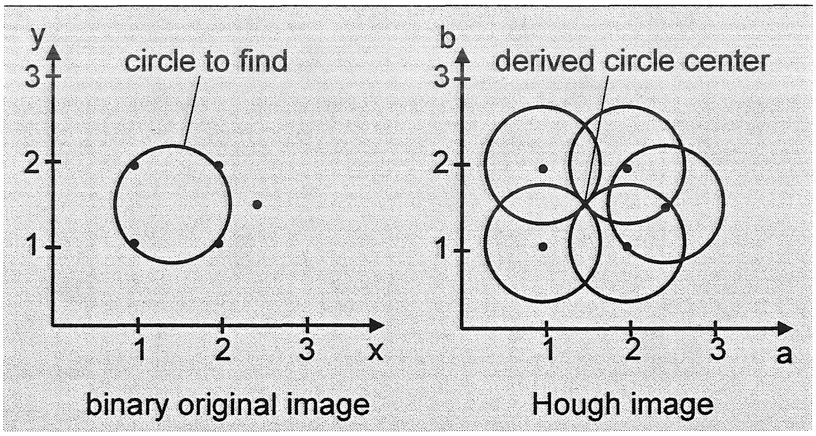

Figure 7: The Hough-transformation uses a parametric description of simple geometrical shapes in order to reduce the computational complexity of their search in a binary edge image.

The Hough-transformation needs to have a diameter value before it can recognise a circle. Because the tree diameter is not known before applying the algorithm we start with a value of 100 cm and reduce the value in increments of 10 cm.

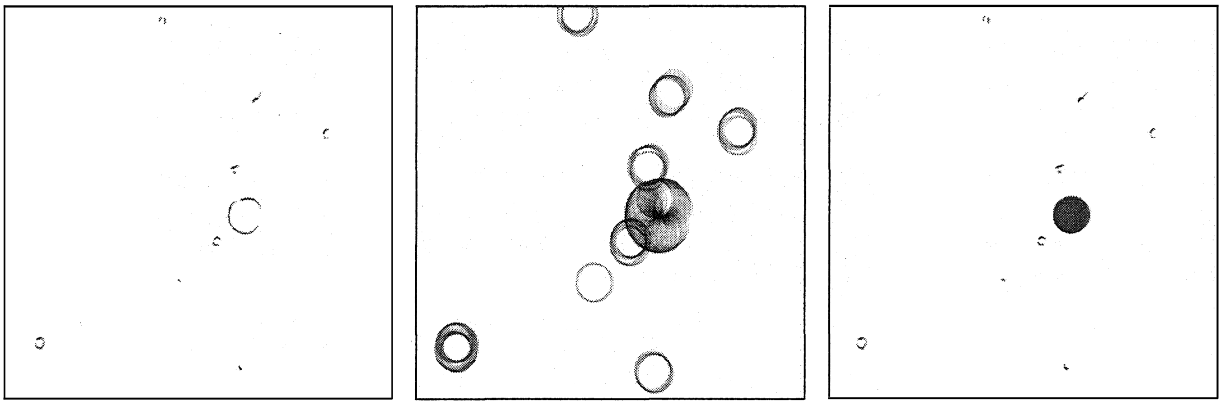

Figure 6a: Binary image layer with `C´ circle ring; b: Hough image; c: Hough circle.

The determined Hough circle is expanded by 10% to ensure the identification of all pixels that could be part of the stem. On the selected pixels an algebraic algorithm is used to fit the circle precisely. The centre coordinate minus 1,30 m is assumed to be the tree stump coordinate and the diameter of the circle is equivalent to the DBH.

RESULTS

In one test area, 28 Douglas- and silver fir trees with a diameter above bark in DBH of greater than 7 cm were measured conventionally. The reference data was measured with a total station (position) and a calliper (two cross-wise measurements in DBH). With the coordinates and DBH we derived using the laser scan data we could correctly identify 26 out of the 28 trees. We consider this very promising. The two trees that could not be identified were densely overlapped by small branches in the direct line of sight from the scanner to the tree. The branches disturbed or blocked the measurement of the trees too much.

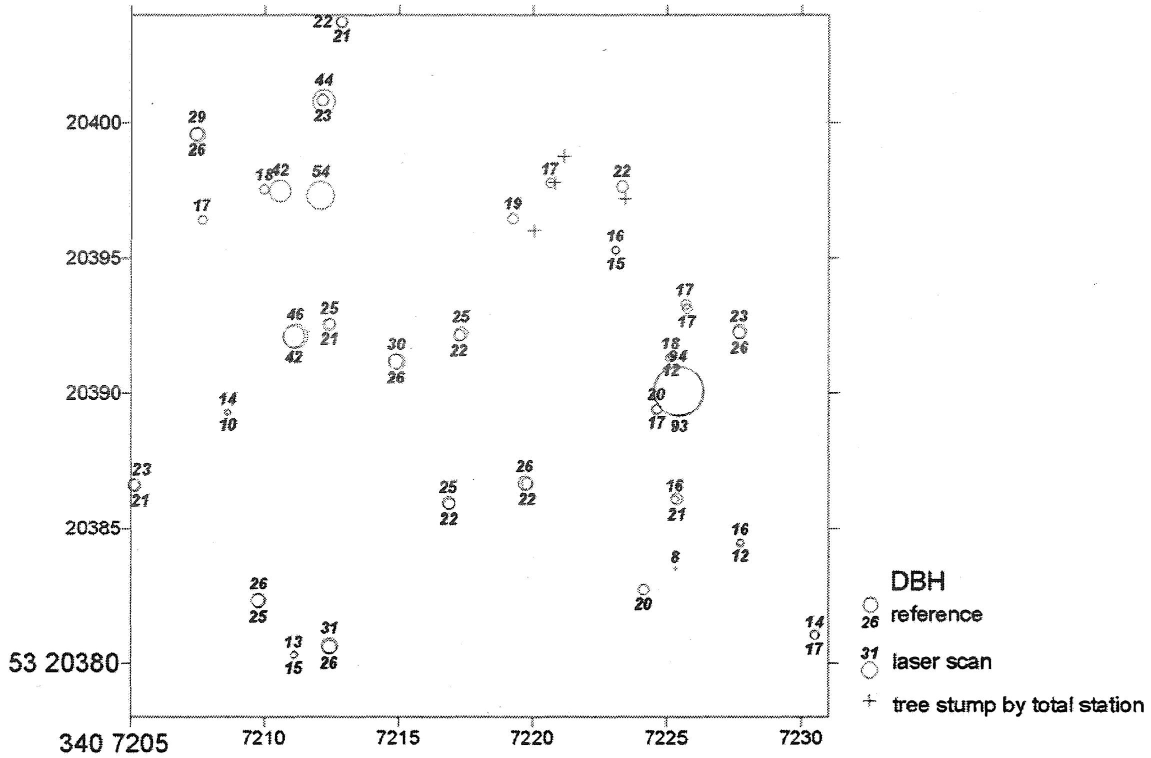

Figure 7: Plot with DBH measured by total station and derived out of the laser scan data.

For two trees the difference between the reference and derived tree reaches up 90 cm. This is due to an extreme sweep close to the base of the stump. Because tree positions are measured at 1.30m height, sweep has a very strong influence on their positions. For all other trees the differences are less than 20 cm.

One of the trees shows a great difference in DBH compared to its reference. Noticeable for this tree is that the circle determined by the Hough-transformation resulted in a more accurate approximation than the circle resulting from the algebraic algorithm that is supposed to be superior.

Table 1: Comparison of the reference data and the results from the laser scan. Originally 28 trees were measured. 26 were automatically identified in the point cloud. Two were excluded because of their sweep and one was excluded because of an error in the algebraic algorithm. The calculated position differences are based on 23 trees.

	min [cm]	max [cm]	mean [cm]	standard deviation (σ) [cm]
Radial position differences	2.0	17.1	5.0	3.6
DBH differences	-5.8	5.6	1.7	2.8

The method used to locate trees in the laser scan identified more trees than were actually present. This effect was caused by a dead tree lying on its side, the thick branches of which were themselves recognised as trees. A repetition of the automatic diameter estimation in upper parts of the bole would help to identify these specific patterns.

CONCLUSIONS

The approach for deriving tree characteristics from terrestrial laser scanner data described in this paper allows an automatic identification of trees, their positions and the DBH (as well as additional diameters in variable tree heights). The results can be used as a basis for further automatic determination of other single tree characteristics such as tree species, tree height, crown projection area as well as location and type of wood defects.

Developed methods and algorithms must be improved, especially the combination of Hough-transformation and algebraic algorithm needs some enhancement. In the near future RGB colour information will be added to the 3D geometry data. This will certainly improve filter methods and also facilitate the determination of other forest inventory parameters, especially wood defects and biomass distribution.

In the future, the main point of emphasis will be to separate information about crown structure from the 3D point clouds, to estimate crown variables such as crown width, crown surface area, etc. and compare them with results derived from airborne laser scanner data as well as conventionally measured crown parameters. In addition, the implemented algorithms should be tested based on just one scan from the centre of the sample plot, so that it is an option to use the terrestrial laser scanner technique for deriving precise 3D models of certain forest stands or for collecting a high number of data from different sample plots as is usual in most national forest inventories.

In addition to the accuracy of the data the great advantage of this technique is to obtain repeatable results of measurements because of the high level of automatism. Effects resulting from subjective influences like different measuring persons, accuracy of a number of different measurement devices etc. are excluded.

ACKNOWLEDGEMENTS

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ESTIMATION OF FOREST STEM VOLUME USING OPTICAL SPOT-4 SATELLITE DATA AND FIELD MEASURED TREE HEIGHT DATA IN COMBINATION

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ABSTRACT

The accuracy of forest stem volume estimation at stand level has been investigated using a combination of multi-spectral optical SPOT-4 satellite data and field measured tree height data. The hypothesis is that the accuracy will be improved for the combined stem volume estimates compared to using SPOT-4 data only. The test site, Remningstorp, is located in the south of Sweden and consists mainly of coniferous forest. At Remningstorp, a laser scanning campaign is planned to take place during the summer of 2003 and laser data will be acquired for the test site. This will give the possibility of investigating the usability of combining multi-spectral optical satellite data and tree height measurements from laser data, at stand level. However, tree height measurements used in this study were collected using an objective inventory method in order to obtain standwise tree height measurements similar to those derived from laser data. The stem volumes for the investigated stands were in the range of 15-585 m^3 ha^{-1} with an average stem volume of 266 m^3 ha^{-1} and an average stand size of 3.5 ha. Regression analysis was used to estimate stem volume at stand level. The results showed a significant improvement for the combined stem volume estimate with a root mean square error of 29.6 m^3 ha^{-1} (11.1% of the average stem volume) in comparison to stem volume estimates found in the literature based on multi-spectral optical SPOT satellite data only. The obtained accuracy is in agreement with previously presented results based on laser data with a relatively dense sample of laser measurements. The results imply that the combination of multi-spectral optical satellite data and tree height data can be used for standwise stem volume estimation in forestry applications.

INTRODUCTION

Remotely sensed data in the form of aerial photos have been used for decades to estimate forest variables in support of forestry management planning. Through manual interpretation of aerial photos using a stereo instrument, stand delineation and estimation of tree species composition and canopy closure could be performed. The stereoscopic view also allows accurate tree height measurements in forest stands if the ground is visible in the photos. Using tree height and canopy closure, standwise stem volume could then be indirectly estimated. A forest stand is considered as homogenous forest in terms of tree cover and site conditions, typically 0.5-20 ha in size. Stem volume, one of the most important variables in forestry planning, represents the trunk volume per unit area (m^3 ha^{-1}) excluding branches and stumps. Aerial photo interpretation is often carried out together with a field inventory to improve forest variable estimation. The photo interpretation and field inventory is based on manual work and relies on the expertise of the personnel involved. In Sweden, the described procedure is known as the National Land Survey method and has primarily been used among the forest companies (Åge, 1985). For stem volume estimation at stand level based on aerial photos the accuracy in terms of standard error is about 15% of the average stem volume (Ståhl, 1992).

For large-scale forest inventories, the advantages of using remotely sensed data are large, especially if objective and automatic methods could be developed to a low cost per area unit. In this context, the possibility of using remotely sensed data from passive (optical) and active sensors (laser and radar) is investigated to directly or indirectly assess forest variables useful for forest management planning. High-resolution laser scanning and low-frequency synthetic aperture radar are sensor technologies that have shown potential for operational use in forestry applications. In this paper, the potential use of multi-spectral optical satellite data and laser scanner data for stem volume estimation is addressed.

In Scandinavia, it has been demonstrated that high-resolution laser scanner data provides accurate estimation of forest variables at stand level (e.g., Hyyppä et al., 2001; Næsset, 2002; Holmgren, 2003). Hyyppä et al. (2001) investigated boreal forest characterised by stem volume in the range of 2-335 m^3 ha^{-1}, reporting standard errors for mean height, basal area, and stem volume of 1.8 m (9.9% of the average mean height), 2.0 m^2 ha^{-1} (10.2%), and 18.5 m^3 ha^{-1} (10.5%), respectively. A study performed by Næsset (2002) was based on coniferous dominated stands with stem volumes ranging from 91-415 m^3 ha^{-1}. The stands were divided into three strata according to age class and site quality prior to evaluation. The standard deviations of the differences between predicted and ground-truth values of mean height, basal area, and stem volume were found to be 0.61-1.17 m, 2.33-2.54 m^2 ha^{-1}, and 18.3-31.9 m^3 ha^{-1} (corresponding to 11.4-14.2% of the average stem volume), respectively. In Holmgren (2003) laser data were used to predict mean height, basal area, and stem volume in coniferous forests with stem volume in the range of 0-600 m^3 ha^{-1}. The accuracy, in terms of root mean square error (RMSE), was 0.59 m (3% of the average mean height), 2.7 m^2 ha^{-1} (10%), 31 m^3 ha^{-1} (11%), respectively, for the best case investigated.

When estimating stem volume using laser data, both the vertical and horizontal structure of the forest vegetation needs to be accurately captured. As the vertical structure (tree height) is measured directly, adequate measures describing the horizontal structure (forest density) need to be derived from laser data. The above reported results rely on a relatively dense sample of laser measurements (up to a few meters between laser footprints). In the scenario of several meters between laser footprints, stem volume is expected to be less accurately estimated due to uncertainty in laser data derived forest density measures. However, standwise mean tree height is still believed to be accurately estimated using low laser measurement density. Given a sparse sample of laser measurements, the forest density may instead be captured using optical satellite data to accurately estimate stem volume at stand level.

Nilsson (1997) investigated the possibility of combining multi-spectral optical Landsat TM satellite data and field measured tree height data to improve estimation accuracy for stem volume. The study was carried out in boreal forests using the *k*NN method at sample plot level. In the evaluation dataset (plot radius of 7 m) the mean tree height and stem volume were 12.9 m and 149 m^3 ha^{-1}, respectively. The result showed that the MSEs for stem volume decreased by 46% (on average) compared to the MSEs observed using Landsat TM data only. Holmgren et al. (2000) also used the *k*NN method to estimate stem volume in boreal forests by combining Landsat TM data with field data. The stem volumes for the stands used as validation dataset were in the range of 0-480 m^3 ha^{-1} (on average 156 m^3 ha^{-1}). The accuracy, in terms of standard error, for the stem volume estimates was found to be 36% of the average stem volume using satellite data only. By adding site index, age, and mean tree height as ancillary data the standard error was improved to 17%.

The objective in this study is to evaluate the accuracy of standwise estimation of forest stem volume using multi-spectral optical SPOT-4 satellite data and tree height data in combination. In the present study, tree height measurements were collected using an objective inventory method in order to obtain standwise tree height measurements similar to those that could be derived from laser data.

TEST SITE DESCRIPTION

The test site, Remningstorp, is located in the south of Sweden (58°30'N, 13°40'E) and covers about 1200 ha of productive forestland (Figure 1). The prevailing tree species are Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and birch (*Betula* spp.). The dominant soil type is till with a field layer consisting of blueberry (*Vaccinium myrtillus*), cowberry (*Vaccinium vitis-idaea*) or narrow thinned grass (*Deschampsia flexuosa*). In the denser forest a field layer is not present. The topography is fairly flat with a ground elevation varying between 120 and 145 m above sea level.

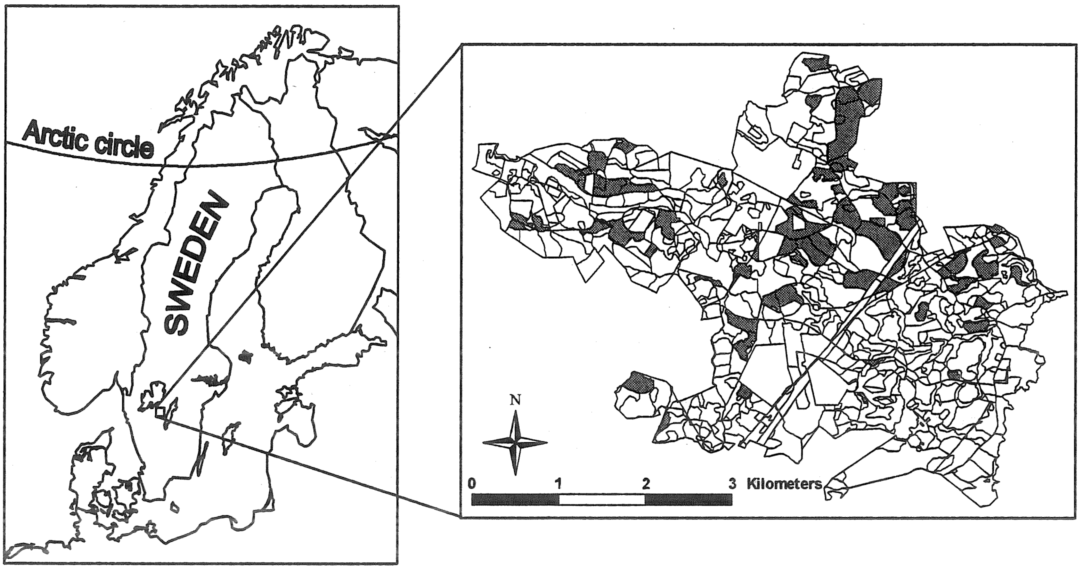

Figure 1: Test site location showing 61 objectively inventoried forest stands (shaded grey).

FIELD DATA

The ground data available for the test site consisted of a digital stand boundary map, a coarse (50×50 m^2) digital elevation model (DEM), and standwise field measurements.

The field inventory was carried out using the forest management planning package (Jonsson et al., 1993). In each stand, sample plots (radius 10 m) were placed in a randomly positioned systematic grid. On each plot all trees were tree species determined and callipered at breast height (i.e., 1.3 m above ground). For randomly selected sample trees, chosen with a probability proportional to basal area, tree heights were also measured. Hence, field data were collected using an objective and unbiased method.

Altogether 106 stands were randomly selected for field inventory assuring that the entire stem volume range was represented in the analysis. The standwise estimated stem volumes from field measurements collected between 1997 and 2002 were adjusted to 2000 to match image data acquisition. For this study, stands were selected to represent coniferous forests with various stem volumes using the criteria of coniferous stem volume >70%, soil type till, and ground slope <4°. The selection criteria were used to obtain a broad range of stem volumes and to keep influencing variables as constant as possible. In total, 61 stands fulfilled these criteria giving stem volumes in the range of 15-585 m^3 ha^{-1} with an average of 266 m^3 ha^{-1}. The stands varied between 0.6-19.2 ha in size with an average of 3.5 ha. On average nine sample plots were measured in each stand. The estimated accuracy, in terms of standard error, was about 9% of the average stem volume at stand level.

OPTICAL SATELLITE DATA

SPOT-4 is a multi-spectral optical satellite orbiting the Earth in a near polar and sun-synchronous orbit at an altitude of about 800 km. The high resolution visible and infrared optical instrument has a green (B1), red (B2), near infrared (B3), and mid infrared (B4) band measuring reflectance represented by digital numbers (DNs) in the wavelengths 0.50-0.59, 0.61-0.68, 0.79-0.89, and 1.58-1.75 µm, respectively. The images cover 60×60 km and the ground resolution is 20 m with a radiometric resolution of 256 digital levels. The optical image used in this study was registered under cloud free conditions on July 3, 2000 with track 053, frame 230/2, view angle -20.8°, and sun elevation angle 52.8°. The image was geometrically precision corrected by the Swedish Space Corporation to the Swedish National Grid with a geometrical error of about 10 m.

METHOD

In order to estimate standwise stem volume a model was developed using linear regression analysis. The set of predictor variables chosen consisted of the average DN of the multi-spectral bands B1-B4, ditto squared, the ratio between the bands, and the objectively inventoried mean tree height, at stand level. In total a set of 15 predictor variables were investigated. The selection of predictor variables to be included in the model was based on residual studies, statistical significance of the estimated regression coefficients, and the coefficient of determination. The model for estimation of stem volume using SPOT-4 data and mean tree height data, at stand level, is expressed as:

$$\ln(v_i) = \alpha_0 + \alpha_1 \mathrm{B1}_i + \alpha_2 \mathrm{B1}_i^2 + \alpha_3 \frac{\mathrm{B1}_i}{\mathrm{B3}_i} + \alpha_4 \frac{\mathrm{B2}_i}{\mathrm{B4}_i} + \alpha_5 \ln(h_i) + \varepsilon_i + \delta_i \tag{1}$$

where v_i is the stem volume in m^3 ha^{-1} for stand i, α_0, α_1,..., α_5 are the regression coefficients, $B1_i$, $B2_i$, $B3_i$, and $B4_i$ are the average DN for stand i, respectively, h_i is the mean tree height, ε_i is the random error for the true stem volume, and δ_i is the sampling error for the ith stand. The random variables ε_i and δ_i were assumed to be independent and normally distributed with zero expectations and variances σ^2_1 = Var(ε_i) and σ^2_{2i} = Var(δ_i). The regression coefficients were estimated by means of ordinary least squares (OLS).

A correction factor for logarithmic bias was applied as the average of stem volume estimated from the field measurements divided by the average of the predicted stem volumes. Furthermore, correction for the sampling error was carried out as described in Fransson et al. (2001). Finally, a cross-validation test was performed to ensure that the function was not overfitted.

RESULTS

The estimated stem volume from field measurements plotted against the combined stem volume estimate from model (1) is shown in Figure 2. All regression coefficients in (1) were found to be significant ($p < 0.001$) except for the intercept (α_0). The regression coefficients were estimated to α_0 = -0.410, α_1 = 0.170, α_2 = -0.004, α_3 = -5.37, α_4 = 3.03, and α_5 = 1.50. The relative RMSE before correction of the sampling error was 13.2% of the stem volume (corresponding to 35.1 m^3 ha^{-1} for the average stem volume) and with the sampling error removed 11.1% (29.6 m^3 ha^{-1}). The coefficient of determination (adjusted) from the regression analysis was 97.6% and the correlation coefficient between stem volume and mean tree height estimated from field measurements for the 61 stands was 0.87.

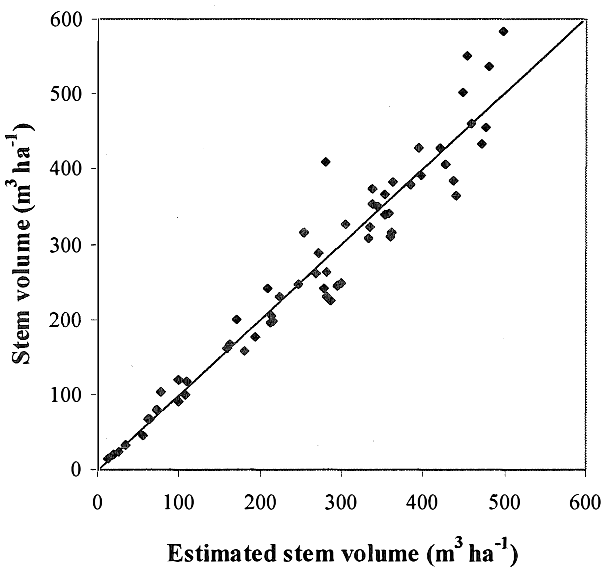

Figure 2: Stem volume plotted against estimated stem volume from a combination of SPOT-4 data and mean tree height data, at stand level, using regression model (1) with a reference line, for 61 objectively inventoried stands.

The square root of the ratio between the estimated total variance about the regression function with cross-validation and the estimated total variance about the regression function without cross-validation was found to be 1.05, which is considered acceptable.

DISCUSSION

In this study, the combination of multi-spectral optical SPOT-4 satellite data and forest tree height data for estimation of stem volume, at stand level, has been investigated using regression analysis. The analysis was based on coniferous forest stands at a test site located in the south of Sweden. The estimation accuracy was expressed in terms of root mean square error (RMSE). Standwise field measured tree height data were used due to limited availability of laser scanner data.

The results show that accurate estimates of standwise stem volume can be obtained with a RMSE of 29.6 m^3 ha^{-1} (corresponding to 11.1% of the average stem volume). The obtained accuracy is in agreement with previously presented results based on laser data with a relatively dense sample of laser measurements (e.g., Hyyppä et al., 2001; Næsset, 2002; Holmgren, 2003). However, standwise mean tree height used in the present study is believed to be accurately estimated using only a sparse sample of laser measurements, which will reduce costs in large-scale forest inventories.

In comparison with studies based on multi-spectral optical satellite data, the results reported by Fransson et al. (2001) showed that stem volume in boreal forests could be estimated with RMSEs of 24-36% of the average stem volume using SPOT data. The study was performed at a boreal forest test site with stem volumes in the range of 0-305 m^3 ha^{-1} (on average 129 m^3 ha^{-1}). Magnusson and Fransson (2003) estimated stem volume at stand level using SPOT-4 data and obtained a RMSE of 23.5% on the same dataset as used in this paper. Hence, by adding standwise mean tree height as explaining variable in the regression analysis the RMSE was improved by about 53% (23.5% to 11.1%). The studies by Nilsson (1997) and Holmgren et al. (2000) also showed a significant improvement when combining multi-spectral optical satellite data with field data.

The next step will be to perform standwise stem volume estimates using multi-spectral optical satellite data and laser data. Further research is needed to investigate the required number of laser measurements per area unit in order to achieve accurate mean tree height estimates.

Replacing the field measured tree height data with laser measured tree height data acquired from a sparse sample of laser measurements, the proposed method may be suitable in large-scale inventories in order to improve cost-effectiveness. In such a scenario, empirical relationships between stem volume and remotely sensed data (i.e., multi-spectral optical satellite data and tree height data measured from laser scanning) need to be developed using a sample of known reference stands. These relationships could then be used to estimate standwise stem volume for each stand using the proposed remote sensing data sources. In addition, optical satellite data may also be used for segmentation of stand boundaries and provide useful information about the proportion of coniferous and deciduous trees.

In conclusion, the results for standwise stem volume estimation were found to be better than using the conventional National Land Survey method, implying that the combination of multi-spectral optical satellite data and tree height data can be used in forestry applications.

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POSSIBILITIES WITH LASER SCANNING IN PRACTICAL FORESTRY

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ABSTRACT

Visual interpretation of aerial photographs or numerical satellite image analyses have shown a capacity for large area forest-mapping tasks, such as the estimation of stem volume, the discrimination of tree species, the classification of site types and forest taxation, and the detection of forest changes. The results, however, have seldom been satisfactory for small area inventories or for operative forest planning. With the development of digital technique, the amount of remote sensing material available for forest inventories increases with escalating pace. Digital aerial photographs, airborne video imagery, spectrometers and ranging radar detection represent the latest in airborne images and compete with dozens of new, more accurate satellite images. One of the most promising alternative of these new technologies for increase accuracy and efficiency of forest inventory is airborne laser scanner data.

The present state of the art in laser scanning indicates high potential in assessing various parameters of single trees, and to adapt this information for plot and stand level. The height of individual trees can be measured at the best with an accuracy of 50 cm. At stand level, basal area and stem volume can be obtained with a standard error of about 10 % if the relation between height and diameter of the tree is solved appropriately. The use of the distribution function can helped in assessing the amount of wood in the second and third storeys. Tree species can be obtained with the help of the aerial imagery to about 80-90 % correctness for individual trees. Using multi-temporal data sets it has been shown that even the plotwise growth of trees can determined with about 10 cm precision using laser scanner (based on 2 years separation in laser acquisitions). The corresponding value for standwise growth is 5 cm. All mature cut or fallen trees can be automatically detected. In addition, laser survey provides a DEM with accuracy between 20-40 cm in hilly, forested areas. In this context, we analyze possibilities of laser scanning data in operative forest planning and in a strategic planning inventory taking into account the information requirements related to wood purchasing as well as increasing needs for ecological information such as measurements of landscape level biodiversity.

1. INTRODUCTION

Detailed and timely information on forests are required by e.g. traditional forest management, forest certification and assessment of forest biodiversity. This increased demand of information combined with the desire to reduce costs have created a need to increase the efficiency of forest information acquisition. Technologies for acquiring spatial forest resource information have developed rapidly during the past years. Field work has been enhanced by satellite positioning systems (GPS), automatic measuring devices, field computers and wireless data transfer. Modern remote sensing, in turn, provides cost efficient spatial digital data which is both spatially and spectrally more accurate than before.

Promising results in generalizing field inventory results to large forest areas using remote sensing have commonly been achieved (e.g. Tomppo 1990, Tokola 1990, Tokola & Heikkilä 1997, Katila & Tomppo 2001, Hyvönen 2002). However, apart from visual interpretation of aerial photos, remote sensing has rarely been used in forest planning compartmentwise inventories. This is because of two main reasons. Firstly delineation of compartment boundaries is a highly subjective matter and thus difficult to accomplish automatically via numerical methods. Secondly the accuracy of numerical interpretation methods has so far not been adequate enough. With the development of digital technique, the amount of remote sensing material available for forest inventories increases with escalating pace. One of the most promising alternative of these new technologies for increase accuracy and efficiency of forest inventory is airborne laser scanner data.

The present state of the art in laser scanning indicates high potential in assessing various parameters of single trees, and to adapt this information for plot and stand level. The height of individual trees can be measured with high accuracy. At stand level, basal area and stem volume can be obtained with a error acceptable for practical forestry if the relation between height and diameter of the tree is solved appropriately. The use of the distribution function can helped in assessing the amount of wood in the second and third storeys. Tree species can be obtained with the help of the aerial imagery. Using multi-temporal data sets it has been shown that even the plotwise growth of trees can determined. Mature cut or fallen trees can be automatically detected. In addition, laser survey provides a DEM with high accuracy in hilly, forested areas.

The cost of laser scanning is relatively high. However, due to the improved availability of the laser scanner and also due to the technological development, the costs of laser scanning are all the time decreasing. Practical forestry today includes the possibilities of using laser scanner for standwise forestry as suggested by Næsset (2002). On the other hand, the development of individual tree characterization proposes possibilities of using such techniques in practical forestry. Due to the present high costs related to individual-tree based solutions, we analyze the possibilities of using laser scanner as a sampling device.

This paper describes a possible practical solution for operative forest data acquisition. We first analyze the technical possibilities related to the laser scanner and then apply that for large area forest inventory.

2. TECHNICAL POSSIBILITIES

2.1 Profile imaging and laser scanning

Profile imaging is aimed to produce height profiles of the imaged objects by imaging the area of interest in parallel flight lines. Since the flight altitude is only 100-200 m a single flight line covers a relatively narrow strip of terrain. A 3D profile of the imaged area can be accomplished by joining several flight line images. Examples of profiling sensors are the laser based LIDAR (light detection and ranging) radar and the profiling microwave radar. According to Hyyppä (1993) a profiling microwave radar is capable of measuring the stock's mean and dominant height, basal area, stem volume, crown height, development class and soil type. The main problem has stemmed from the low ground width of the images. The resulting flight line density in operative use has been so high that imaging costs have soared out of bounds.

Laser *scanning* provides more promising imagery than profile imaging. This technique makes it possible to reach even the single tree level in forest imaging. A laser scanner emits an optical / infrared laser pulse perpendicular to the flight line. Each image row consists of pixels representing almost adjacent ground elements. The x, y and z coordinates are derived for each pixel. By analysing these measurements both 3D terrain and crown models can be derived. The difference of these models is the height model of the stock. The main advantage of this technology compared to optical remote sensing is that in this case the physical dimensions of the imaged objects are measured directly. Ground reference measurements are therefore not required which in turn reduces the total measuring costs (Hyyppä & Inkinen 1999).

2.2. Assessing forest stand attributes by use of laser scanner

2.2.1 TREE HEIGHT MEASUREMENTS

In Hyyppä and Inkinen (1999) and Hyyppä et al. (2001), it was demonstrated that high-pulse-rate laser scanners are capable to detect single trees in boreal forest zone. It was shown that tree heights of individual trees in the dominating storey could be obtained with less than 1 m standard error. However, the results shown in Yu et al. (2003) suggests that better accuracy than 50 cm can be obtained with high sampling density airborne laser scanners. In the Table 2 of Yu et al. (2003), standard deviation of height estimates between two laser acquisitions are given. If all the trees are growing at the same rate within the same stand, the standard deviation also describes the standard deviation of the height estimation divided by $\sqrt{2}$. This implies that even an accuracy of 20-30 cm can be obtained for single tree heights. This is better than the accuracy obtained with conventional hypsometers. Several other studies have also indicated that the mean height can be predicted accurately using laser scanning (Naesset 1997, Magnussen and Boudewyn 1998).

2.2.2. Tree species recognition

Holmgren and Persson (2003) have shown that airborne laser scanning, measuring structure and shape of tree crowns, could be used for discriminating between spruce and pine. The portion correctly classified trees on all plots was 95 %.

2.2.3 Estimation of tree parameters for individual trees

Persson et al (2002) showed that 71 % of the trees could be correctly detected using laser scanner, however, 91 % of total stem volume was detected. The segmentation was improved on fitting a second-order parabolic surface to the height data.

2.2.4 Growth and harvested trees

The applicability of small footprint, high sampling density airborne laser scanner for estimation of forest growth and detection of harvested trees was demonstrated in Yu et al. (2003). Two laser acquisitions - one in September 1998 and another in June 2000 - were carried out using Toposys-1 laser scanner in test site (Kalkkinen), 130 km north of Helsinki. Three-dimensional tree height models were calculated for both data sets using raster-based algorithms. Object-oriented algorithms were developed for detection of harvested trees and forest growth estimation. Out of 82 field-checked harvested trees, 65 trees could be automatically detected. All mature harvested trees were detected; problems were encountered mainly with smaller trees. Forest growth was tested at tree, plot and stand levels. Applied methods included an object-oriented tree-to-tree matching algorithm, interactive orientation using point cloud and statistical analysis. The precision of the estimated growth, based on field checking or statistical analysis, was about 5 cm at stand level and about 15 cm at plot level. The authors expected that the methods may be feasible in large area forest inventories where permanent sample plots are used; the described methods may be applied to replace a large number of permanent plots with laser scanning techniques.

2.2.5 Quality of stem

The objective the study by (Pyysalo and Hyyppä, 2002) study was to carry out reconstruction of single tree crowns from laser scanner data to use the obtained vector model for feature extraction. The reconstruction was implemented in several stages. In the study it was found that dense laser scanner data detail describes the upper canopy of forest and therefore is suitable for tree height information extraction. The lower crown was found less detail measured with laser scanner and parameters extracted from that part were less accurate, but trend setting. Even though, the crown base line was less accurately determined, such information may be used to detect crown base line giving information on the quality of the stem.

2.2.6. Digital Elevation Model (DEM)

Hyyppä et al. (2000) obtained an average standard error for DEM in the forest area of about 22 cm. The accuracy of various DEM algorithms was tested by Ahokas et al. (2002), and an accuracy of 14 cm in a hilly, forested environment was obtained. Information on DEM can be used to further estimate growth, determine good routes for forest road network.

2.2.7 Suppressed Trees

Maltamo et al. (2003) proposed the use of theoretical distribution functions to account for the suppressed trees. The tree crown segmentation method used cannot detect suppressed trees from a height model based on laser scanning. Consequently, the shortest trees of the dominant tree layer may not be recognized. These trees can be predicted by using theoretical distribution functions.

2.2.8 Biodiversity

The three commonly referred components of biodiversity are genetic, species, and habitat (ecosystem) diversity. Habitat composition of a forest area reflects its species richness. Geographic information systems (GIS) and remote-sensing techniques are now increasingly used to study the distribution of animal species based on habitat distribution. Holopainen (1998) developed habitat classification system for the estimation of habitat diversity using airborne images.

By tradition, biodiversity conservation has been focused on protecting individual threatened species, however, this species-by-species approach is expensive and inefficient. Due to the complex relationships between species and their biotopes, a biotope approach to the conservation of biodiversity is often preferable. Of the many means of describing vegetation diversity, the most common are extent, structure, composition, biomass or production, and condition. Each of these can be assessed on the ground, but they may be assessed more effectively from various forms of remote-sensing data.

Several digital image features can be used in numerical classification and in the assessment of the diversity of a forest (Parmes 1996). The features can be derived from the digital numbers of single pixels, segments, or groups of segments. Traditionally, texture has been divided into statistical and structural texture (Haralick 1979). Statistical texture can be understood as the randomlike variation of tone values in the neighborhood, while structural texture quantifies the structure, form, and location of pixels or segments. If geometric, contextual, and pattern features are used, presegmentation of the image is needed. Presegmentation divides the image area into units of homogeneous tone values. Once the image has been segmented, geometric features such as the size and shape of land cover units and their distribution can be calculated. The frequency of segment boundaries describes the texture or diversity of a landscape. In contrast, the ratio of the size of the segments to their boundary lengths is correlated with the complexity of the landscape (Parmes 1996). When the structure becomes more clear and shows better spatial resolution, it is possible to use structural contextual features, in which the units are homogeneous stands, or labels of a group of stands. If location of these stands is known, spatial heterogeneity can be characterized by fragmentation. In practice, the natural distribution of ecosystems is heavily fragmented, mainly as a result of human intervention.

The fragmentation of a forest area can be characterized by using some simple metrics of landscape, e.g. biotope areas, density, size, and variability. Edges, shapes, core areas, and nearest neighbors can also be used as indicators of landscape diversity. A group of diversity indices exists, traditionally used in the assessment of species diversity, that can also be used to determine landscape diversity.

Holopainen (1998) studied Forest habitat mapping by means of digitized aerial photos and multispectral airborne measurements. The habitat classification used aimed to compress tree stand and ground vegetation information into a single variable. Classification based on tree and ground vegetation. Holopainen (1998), Holopainen & Wang (1998a) and Holopainen & Jauhiainen (1999) found out that habitats derived by tree information were possible to identify with high accuracy using numerical interpretation of aerial photographs. However, when accounting ground vegetation, the classification accuracy was decreased remarkably (Holopainen & Wang 1998a, Jauhiainen et al. 2003).

Laser scanning has advantage compared to interpretation of digital aerial photograps by having possibility to detect measurements also from ground vegetation and under storey. That means it would be possible to derive valuable information also for calculation of landscape level biodiversity indices and indicators.

The tree height maps of the forests can also be used to preserve biodiversity. E.g. Russian flying squirrel is rare within the European Commission and special actions are carried out to preserve the habitat. It is possible to selectively harvest the trees and still leave transition areas for the squirrels within the road construction processes.

3. PROPOSED SCENARIO

Presently, the availability of the laser data is significantly improving each year and the costs are steadily decreasing due to the acceptance of new systems with higher sampling density and higher flight altitude. Most of the presently available laser systems can detect individual trees. Present costs for laser survey are highly dependent on the size and shape of the test site. The most economic use of the laser scanning in forestry is to apply it on a strip-base sampling, since long stripes are economic to fly. Thus, large-area forest inventory using permanent or non-permanent sample plots are perhaps the most feasible operative applications for laser scanning at single tree level. Furthermore, Laser scanning sample could be utilized in compartment-wise forest inventory if some cheaper remote sensing material (e.g. digital aerial photographs) is available for generalising laser scanning result to whole forest area.

Thus, in addition to the laser scanner flight, we recommend the use of a separate aerial survey, to help in the tree specie classification and for generalising. Laser scanner survey is recommended to be repeated every 8-10 years. The use of theoretical distribution functions is suggested to account for the suppressed trees.

The obtainable parameters for the plot are the following:

1. Individual tree heights and mean tree height
2. Percentage of crown coverage, crown area for each tree, basal area, mean basal area, mean diameter
3. Stem volume of each stem, mean volume
4. Tree species
5. Number of stems
6. Growth (individual tree height crown, crown growth, mean volume growth)
7. Quality of the stems
8. Site quality and fertility (from the growth data)

4. DISCUSSION OF THE SCENARIO

4.1 Example

Let's take a forest inventory example. In the following, we compare costs of traditional compartment-wise forest inventory to airborne laser scanning based inventory. The selected study area is virtual company Forest Ltd situated in central Finland. Forest Ltd. has about 200 000 ha forest that should be inventoried. Because full coverage of laser scanning might be too expensive for forestry purposes, our starting point is a multi-phase sampling involving laser scanning, digital aerial photographs, and field measurements. Sufficient laser scanning sample would be 10 % of forest area, that is 20 000 ha (200 km^2) in our example. If our area is 40 km x 50 km square and flight line widht is 200 m, we should have 20 flight lines each 50 km in length.

The processing of the laser data has the following steps: 1) tranformation of the data to local coordinates, 2) classification of the point cloud into underground hits, ground hits and vegetation hits, 3) calculation of the DEM and DSM corresponding to crown level, 4) calculation of the 3-D tree height model, 5) segmentation of the tree height model, 6) derivation of the treewise parameters from the laser data and digital aerial photographs 7) derivation of plotwise statistics as well as generalization of the data for aerial photographs.

In tree level analyses tree crown models are derived using either digital photogrammetry of aerial photos or laser scanning. In our example, tree heights are derived using laser scanning sample, tree species and crown size by means of aerial photographs, and other tree characteristics using various tree models. Successful implementation of this approach requires successful tree crown identification especially in two-storey and multi-storey stands and appropriate tree models. Theoretical models taking into account trees invisible on the remotely sensed imagery are also required in order to achieve unbiased analysis results.

Single-tree-based inventory is applied for the whole laser scanning data. Typically, automatic segmentation leads to 50 % correctly classified segments and also 50% of the existings trees is assumed to belong to the dominating storey. This means that by fully automatic techniques, 25 % of the trees existing in the surveyed area are collected and processed. This means, that by the laser survey, we can collect 2.5 % sample of all the trees in the Forest Ltd. test site.

Laser scanning sample would be generalized to study area by digital aerial photographs. Numerical interpretation of digital aerial photos has been hindered by radiometric irregularities in the imagery. Issues related to e.g. the atmosphere, central projection, sun angle, topography, film properties, and camera optics cause bi-directional reflectance effects which makes similar objects in different parts of image differ greatly in respect to their image features. This phenomenon causes difficulties even in visual interpretation and is especially problematic in numerical interpretation which is commonly based on the stratification of image features into homogenic classes or strata. Empirical and semi-empirical correction methods have been applied quite successfully with digital aerial photos (Holopainen & Wang 1998a, 1998b, Pellikka 1998, Holm 1999, Mikkola & Pellikka 2002), video imagery (e.g. King 1995) and spectrometer imagery (e.g. Leckie et al. 1995).

Traditional pixel-by-pixel image analysis is not applicable when employing very high spatial resolution (VHR) image material because the size of a pixel is typically smaller than the object of interest. As a solution to the determination problem segment -based approach in which image segments serve as units of feature extraction and image analysis has been suggested (e.g. Pekkarinen 2002). Segmentation divides the image completely into continuous, non-overlapping homogeneous sets of pixels (Pekkarinen 2002).

Here, we suggest automatic segmentation of empirically corrected digital aerial photographs. Segments can be used as units of feature extraction. Laser scanning sample can be generalized to segments using k –nearest neighbour (*k*-NN) estimator. Feature space would consist of segment-based spectral and textural features.

4.2 Comparison of the costs of laser scanning and aerial photography versus conventional compartment-wise forest inventory

Since there are not any laser scanner in Finland, the costs of the laser scanning flight would consist of the mobilisation and survey costs. That would be 12 000 Euro for the mobilisation and roughly 40 000 – 50 000 Euro for the data acquisition and preprocessing. It is assumed that full coverage of aerial photography is collected as standard procedure of forest inventory. In the following, we estimate that the total costs of laser surveys are 60 000 Euro, which means 3 Euro per hectare of collected data and 0.3 Euro per hectare for the whole inventory area. Additional 60 000 Euro would be needed for the processing of the laser data into location-based tree-wise information Therefore, the additional costs of laser scanning is 0.6 Euro per hectare. Another survey after 8-10 years would cost the same amount.

Aerial survey that is used for tree species recognition and for generalising the laser scanning sample to whole forest area is, of course, more expensive when flying lower. If our aim is to make tree-wise measurements (tree species) using aerial photos, scale of 1:16 000 or better (Korpela 2000) is required. If our goal is compartment-level segmentation smaller scale (e.g. 1:30 000) is enough. In our example, we would like to make tree-wise estimations, i.e. we use photos that are photographed at the scale of 1:16 000. Preprosessing (radiometric correction and segmentation of about 300 aerial photos) and estimation of results to whole forest area would cost approximately 300 € / photo, i.e. 90 000 €. The cost of the (ortho)photos would be about 200 € / photo, i.e. 60 000 €.

In traditional forest inventory, the cost for permanent sample plots are normally 100 $ per plot. In 2000, total costs of compartment-wise inventory in Finland was 17,9 € / ha, in which about 45 % (7.9 € / ha) is cost of field measurements (Uuttera et al. 2002). The usability of laser scanning based inventory in practise is dependent on amount of field work.. Assuming the accuracy of laser scanning data in estimating forest variables such as tree hight, diameter, basal area, and volume of trees is as high as in previous research, and that accuracy of tree species recognition using digital aerial photographs is sufficient, volume of stand, tree species and timber assortment distributions would be possible to estimate without field measurements. In addition, growth of the trees and site quality would be possible to measure using multi-temporal laser scanning data.

However, field measurements would still be needed in assessing biodiversity indicators and key biotopes. In our scenario, it would be possible to map potentially important areas of biodiversity using tree height maps estimated by laser scanning or using fragmentation indicators estimated by digital aerial photographs. Field measurements can be concentrated to those areas, and e.g. guided transect sampling (Ringvall 2000) could be utilized.

Modern measuring equipment provide a worthy means also for improving the efficiency and accuracy of field measurements. Today field measurements are carried out with the aid of field computers and satellite positioning systems with which measured forest data can be transferred directly to forest databases attached with accurate positioning data. Devices for improving the efficiency and accuracy of stock measurements have also been developed. The Helsinki University Dept. of Forest Management has e.g. developed a new stock measurement device called the laser-relascope which is based on laser measurements of angles and distances. The device can be used to measure tree heights and tree diameters at arbitrary heights from plot centers without actually visiting the trees. All measurements are further positioned using GPS (Laasasenaho et al. 2002).

If we assume, the field measurements are needed in 20 % of forest area, and that the costs of measurements is more expensive than in traditional compartment-wise inventory (about 10 € / ha), the costs of the field work would be 400 000 € in our example. In Table 1, costs of laser scanning based inventory are compared to costs of traditional compartment-wise inventory.

Table 1, costs of laser scanning based inventory are compared to costs of traditional compartment-wise inventory.

Laser scanning based inventory	**Traditional compartmentwise inventory**
laser scanning 60 000 €	
processing of laser scanning data 60 000 €	
Digital aerial photos 60 000 €	
Pocessing of aerial photos 90 000 €	
Field Measurements 400 000 €	
Total costs 670 000 € (3.35 € / ha)	3 600 000 € (18 € / ha)

4.3 Other possible application of laser-derived individual information

Extracting information needed in forest models - The correct delineation of single crowns is the basis for most of the other information which can be derived from laser scanner data. It is also basis for the information needed for most of the forest and meteorological models. An automated procedure to assess single crowns is a decisive step towards a better database for the models and, therefore, a remarkable increase in model quality. Single crown information until now is very difficult to assess. With terrestrial methods, the time consuming procedure is in most cases feasible only for sample plots. Based on the single tree information distribution, diversity or statistics can be calculated. Most of this information is needed in forest related models but is not available today.

Updating of location-based single tree maps, especially in park and city areas. Single trees, parks and gardens are an essential part of the urban environment. Information on trees and forested areas (e.g. parks) is needed for city mapping and modeling. In large-scale map databases single trees are normally stored as points and presented in the map with symbols describing the type of the tree, e.g. a coniferous or a deciduous tree. Larger groups of trees and gardens are presented with symbols inside an area or on a line (a row of trees). It is possible to automatically update these tree maps.

Preservation of ecological corridors - The tree height maps of the forests can also be used to preserve ecological corridors. E.g. Russian flying squirrel is rare within the European Commission and special actions are carried out to preserve the habitat. It is possible to selectively harvest the trees, e.g. in the road construction process, and still leave ecological corridors that anables squirrels to fly across the road to the opposite site of the forest.

5. SUMMARY

When considering remote sensing in forest inventories one must weigh its costs and benefits. How big are the reductions in field work costs compared to the costs stemming from the acquisition, pre-processing and interpretation of the remotely sensed imagery. If remote sensing is regarded beneficial the next step is to consider the type of remote sensing to be applied. Will the imagery be acquired by satellites or aircraft and what is the most suitable spatial, spectral, radiometric, and temporal resolution of the imagery. These issues deal with the size of the inventory area, purpose of the inventory (mapping, monitoring), desired level of accuracy (region, compartment, tree) and image costs. In other words, if the purpose of the inventory is say to locate highly stocked areas for wood purchasing purposes highly detailed information may not necessarily be required. In this case the use of moderate cost mid-resolution imagery (e.g. Landsat) may be recommended. On the other hand, if the purpose of the inventory is to assess within compartment variation or single tree characteristics very high resolution satellite data, digital aerial photographs or laser scanning data is required.

The paper presented a feasible concept and an example of using a laser scanner data as a sampling device for large-area forest inventory. It was assumed that with 10 % coverage, additional cost will be 0.6 Euro per hectare due to laser mobilization, acquisition, preprocessing and processing into treewise information using single-tree approach. Total costs of compartment-wise inventory would be approximately less than 4 € / ha when using laser scanning, digital aerial photos and directed field measurements.

There are currently huge number on-going research projects involving development of new geographical information acquisition methods in forestry, e.g. the use of digital aerial photograps or laser scanning in forest inventory. For example, "Forests in GIS" *post-graduate school* run at the Helsinki University Dept of Forest Management is focused to these issues. It is therefore quite reasonable to expect good results in the present day aspirations to produce more detailed forest information at a lower cost for various forestry related purposes. It however remains to be seen will emphasis be put on the utilization of new remote sensing techniques or on the rethinking and reorganizing of the actual inventory and planning processes.

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