J. W. Gottstein Memorial Trust Fund

The National Educational Trust of the Australian Forest Products Industries

GOTTSTEIN TRUST

APPLICATION OF AIRBORNE LiDAR IN FORESTRY IN NORTH AMERICA AND SCANDINAVIA

JAN ROMBOUTS

2006 GOTTSTEIN FELLOWSHIP REPORT

Joseph William Gottstein Memorial Trust Fund

The Joseph William Gottstein Memorial Trust Fund was established in 1971 as a national educational Trust for the benefit of Australia's forest products industries. The purpose ofthe fund is *"to create opportunities for selected persons to acquire knowledge which will promote the interests of Australian industries which use forest products for the production of sawn timber, plywood, composite wood, pulp and paper and similar derived products."*

Bill Gottstein was an outstanding forest products research scientist working with the Division of Forest Products of the Commonwealth Scientific Industrial Research Organization (CSIRO) when tragically he was killed in 1971 photographing a tree-felling operation in New Guinea. He was held in such high esteem by the industry that he had assisted for many years that substantial financial support to establish an Educational Trust Fund to perpetuate his name was promptly forthcoming.

The Trust's major forms of activity are:

1. Fellowships and Awards - each year applications are invited from eligible candidates to submit a study programme in an area considered of benefit to the Australian forestry and forest industries. Study tours undertaken by Fellows have usually been to overseas countries but several have been within Australia. Fellows are obliged to submit reports on completion of their programme. These are then distributed to industry if appropriate. Skill Advancement Awards recognise the potential of persons working in the industry to improve their work skills and so advance their career prospects. It takes the form of a monetary grant.

2. Seminars - the information gained by Fellows is often best disseminated by seminars as well as through the written reports.

3. Wood Science Courses - at approximately two yearly intervals the Trust organises a week-long intensive course in wood science for executives and consultants in the Australian forest industries.

Further information may be obtained by writing to:
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Jan Rombouts has worked in the field of forest resource assessment and planning since graduating from Ghent University (Belgium) in 1987. After working in management inventory of Sri Lankan mahogany plantations, the National Forest Inventory of Indonesia and the Growth and Yield Clearing House in Samarinda, East Kalimantan he took up a position in the Resource Planning section of ForestrySA in 1998. In 2000 he was appointed Manager, Resource Planning, a position he still holds today.

In 2002 ForestrySA acquired some LiDAR data for experimental purposes. After a rather long incubation period this eventually led to the commencement of part-time post-graduate studies at the University of Melbourne in November 2005. His PhD research topic is “Application of airborne LiDAR to Site Quality assessment in South Australian radiata pine forest”.

Acknowledgements

I would like to thank the Gottstein Trust to grant me a wonderful opportunity to broaden my understanding of a discipline I have taken a particular interest in.

To the many people overseas who have extended a warm welcome and given generously of their time: a big thank you.

My employer ForestrySA has supported me throughout the pursuit of this project.

And my wife and children have gracefully put up with my absence and absent mindedness.

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Acronyms of institutions visited

CFS:	Canadian Forest Service
METLA:	Forest Research Institute Finland
PFC:	Pacific Forestry Centre
QU:	Queens University
SLU:	Swedish University of Agricultural Sciences
TAPIO:	Forest Development Centre Finland
UBC:	University of British Columbia
UJ:	University of Joensuu
UMB:	Norwegian University of Life Sciences
UQAM:	Université du Québec
USFS:	United States Department of Agriculture Forest Service
UW:	University of Washington

Executive Summary

Airborne laser scanning, also known as airborne LiDAR (Light Detection and Ranging), is a remote sensing technology with a proven track record in 3D land surface surveying. The laser's ability to penetrate dense forest cover offers a significant advantage compared to photogrammetric techniques when mapping the topography of forested terrain. Research over the past 20 years has shown that LiDAR data carries information about the horizontal and vertical structure of forests. Methods have been developed to extract this information and practical applications are starting to find their way into the forest industry.

Several Australian forest companies are conducting pre-operational LiDAR trials. At some point these companies may be faced with the difficult decision to substitute radically different LiDAR-based solutions for time-tested conventional methods.

The objective of this study tour was to travel to North America and Scandinavia and to seek out the people and institutions at the forefront of LiDAR research, development and implementation, to see examples of successful transitions from research to operational deployment, to hear about costs and benefits of LiDAR solutions, and perhaps to catch a glimpse of the future as it is being shaped in research laboratories.

Examples of operational use of LiDAR were encountered in Canada and Scandinavia. The main applications were operational planning (road building, harvest scheduling) and forest inventory. Types of information produced included digital elevation models, canopy height models, stand inventories by species with estimates of stocking, mean diameter, basal area, volume and most recently, diameter distributions and even individual tree information.

LiDAR-derived information was generally reported to be superior in terms of accuracy and versatility compared to existing practice. In Canada the investment in LiDAR data was paid back within two years owing to higher net revenue per cubic metre harvested. Prices for stand level inventory inclusive management plans ranged A$12-23 per hectare in Norway, Sweden and Finland. Because it is of very high spatial resolution, LiDAR-based resource information is considered to be useful at a strategic as well as at an operational level, and more easy to update as operations progress in the field. To the Finnish Ministry of Agriculture and Forestry a major advantage of LiDAR-based inventory is the opportunity to reassign staff from field data collection to customer service.

The business model that appears to be developing overseas is one whereby forest companies or associations of forest owners are contracting part or all of the assessment projects out to service companies specialised in LiDAR forestry applications. In Scandinavia at least three such companies are actively competing for business and this should have a positive impact on product and service range, as well as price.

Each of the countries visited has large research teams working on a broad range of topics. Some of the research seeks to optimise existing methods and may lead to cost savings through more efficient use of inputs. Other research is focused on development of new methods and capabilities and may add to the range of uses for LiDAR data. Improved estimation of product assortments and capturing of information useful for environmental management purposes (sustainability indicators, wild life habitat, valuable trees) are high on research agendas.

As always the relevance of overseas experience to the Australian forest industry must be carefully assessed.

Many of the applications which have been operationally deployed overseas have been successfully demonstrated at a research scale in Australia. As a general rule LiDAR applications become more technically feasible as the complexity of the terrain, forest structure and species composition decreases. In Australian even-aged, single-species plantation forests the extraction of a piece of information, say stand volume per hectare, should be less complex than in the mixed-species, mixed-structure forests of Canada and Scandinavia.

It is less clear whether LiDAR-based inventory can match the outcomes of Australian product-oriented inventory systems. It is undoubtedly possible to meet information requirements of forest growers that do not have to worry about product differentiation, for example as in short-rotation plantation forestry for pulp-wood production. However, LiDAR-based inventory has not been demonstrated to provide the product assortment information that forest growers who market products differentiated based on quality and size have come to rely upon. Australian researchers should contribute to the research effort that is currently in progress worldwide to prove that it is (1) technically and (2) financially feasible to do this.

In Australia the decision to adopt LiDAR technologies will be made by individual companies based on internal cost-benefit analysis. This analysis must take into account the many possible uses and immediate/future benefits LiDAR data will be offering. What benefits can be derived from having spatially explicit information i.e. precision forestry? LiDAR will free up staff at a time when the labour market is tightening. Staff will spend less time in the field and on the road. Their focus will shift from collecting the data to adding value to the data. Companies should coordinate data acquisition to reduce per hectare data costs. Data requirements may decrease as methods move closer to an operational optimum thanks to research and experience. LiDAR data prices are predicted to decrease as LiDAR system capabilities increase.

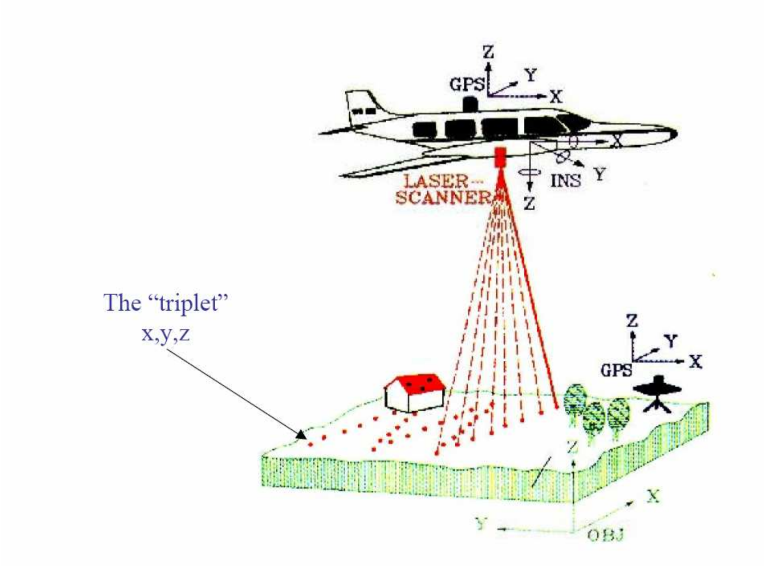
Australian forest companies may find it harder to introduce LiDAR technology than their counterparts in Scandinavia. At the present time there are no specialised service companies offering neatly-packaged LiDAR solutions. Software tools are only in a development stage. Research capacity and expertise is fragmented over many academic, research and forest organisations.

The good news is that two large and several smaller LiDAR data providers are operating in Australia ensuring availability of LiDAR data. Several forest companies have already embraced LiDAR for digital elevation modelling purposes. Several more have invested in pre-operational trials of LiDAR forest mensuration and are getting encouraging results. The next step is to implement successful applications operationally.

Introduction

Airborne laser scanning, also known as airborne LiDAR (Light Detection and Ranging) is an active remote sensing technique designed to measure the 3D surface of the earth. Figure 1 illustrates the 3 main sub-systems of an airborne LiDAR system.

Figure 1: Airborne laser scanning



(from Spencer B. Gross, Inc. web site; adapted from Flood and Gutelius, 1997, PE&RS)

The laser scanner determines distance between aircraft and a point on the earth's surface based on measured time difference between emission of a light pulse and reception of the reflected signal. It also measures the scanning angle. The Global Positioning System (GPS) measures the position of the aircraft relative to the earth. The Inertial Navigation System (INS) measures the attitude of the aircraft (roll, pitch, yaw). By combining distance, scanning angle, aircraft position and attitude the exact x,y,z coordinate of the point on the earth's surface can be calculated.

The best known and most widely used application of airborne LiDAR is topographic terrain mapping, corridor mapping, coastal mapping and depth sounding, and city modelling. Large elevation mapping projects are taking place in many parts of the world, including in Australia. LiDAR is particularly suitable for topographic mapping of land under forest cover because laser pulses can penetrate to the forest floor through small gaps in the canopy.

As soon as LiDAR systems became available researchers started looking at the light pulses bouncing off various forest vegetation surfaces, suspecting that these light pulses carried information about the height, the density and the vertical distribution of the forest. This research which began in the early eighties has continued unabated and has generated ample proof that airborne LiDAR can be used to measure attributes of forests such as height, stocking, diameter, volume, biomass, crown density, canopy structure, Leaf Area Index,…, and the list is still growing as will be shown in this report. It also has given rise to a range of practical forest mensuration applications which in some countries have found their way into the forest industry.

Thus far only topographic mapping has been operationally adopted by forest companies in Australia. The first company to do so was Forest Plantations Queensland (then Department of Primary Industry Queensland). The author's employer ForestrySA is currently participating in a regional 2.8 million ha project to produce a high precision Digital Terrain Model of the upper and lower South-East of the State of South Australia.

Several forest companies (Forests NSW, Forestry Tasmania, ForestrySA) are in advanced stages of pre-operational trials of LiDAR-based forest assessment applications. ForestrySA is undertaking a substantial pre-operational trial of LiDAR-based Site Quality assessment (sub-compartment level volume mapping) of unthinned radiata pine plantations. If the trial is successful LiDAR-based Site Quality assessment could be operationally adopted, leading to the discontinuation of a conventional practice with a 60 year proven track record. This is a big decision to make indeed as it has to take into account technical feasibility as well as financials, logistics, human resources and risk. Under those circumstances much can be learned from others who have chosen a similar path.

The purpose of this Gottstein study tour was to travel to North America and Scandinavia and to:

- visit some of the people at the forefront of LiDAR research, development and implementation overseas;
- see examples of successful transitions from research to operational deployment;
- hear about costs and benefits of LiDAR solutions;
- gauge the vitality of airborne LiDAR research and to get an indication of what the future may bring;
- learn more about tools being used or under development;
- meet people and make contacts.

An itinerary was designed around these objectives (see Itinerary chapter). This report aims to stay as close as possible to the information gathered during the study tour. People met during the tour are introduced in the Itinerary chapter. People quoted are mentioned in the text. Literature and web resources were only consulted to get background information on persons, institutions and countries visited or to flesh out some of the facts mentioned during interviews. Several people, unknown to the author before the study tour or unavailable during the study tour, were contacted upon return. The "Examples of operational use of airborne LiDAR" and "Research and development" chapters of the report relate the information gathered during interviews. The "Relevance to Australian Forestry" chapter is the author's attempt to relate the information to the Australian context.

A discussion of technical aspects and methods of airborne LiDAR is outside the scope of this report. Michael Lefsky of the University of Colorado wrote an very readable introduction to the topic (Lefsky, 2002) available at (http://www.serc.si.edu/labs/forest_ecology/Publications/LefskyEtAl2002b.pdf Another web-based review paper is by Juha Hyyppä et al, 2004 (http://www.isprs.org/commission8/workshop_laser_forest/HYYPPAE.pdf). Of course there is much more material available on the web and a good place to start is in the archives of the International Society of Photogrammetry and Remote Sensing (www.isprs.org).

Examples of operational use of airborne LiDAR in forestry

Many airborne LiDAR applications have been demonstrated in a research context. Few have been comprehensively validated. Even fewer have made it into operational use. One of the objectives of the study tour was to look out for examples of operational use of LiDAR by forestry organisations. Results are presented for each of the countries visited.

United States of America

The USA has about 198M ha of productive forest (timberland). About 58% of this is owned by more than 9 million non-industrial forest holders, 13% by the forest industry and the remainder by the USDA Forest Service and other public owners. Forest ownership is predominantly public on the western half of the country and private on the eastern half. Private forest land produces 92% of harvested timber (Smith et al, 2004).

The United States has a National Forest Inventory program carried out by the Forest Inventory and Analysis unit (FIA) of the USDA Forest Service. This program provides information for national level strategic planning and policy making.

Management planning is not compulsory and is not subsidised. According to a 2002 study (Lindstad, 2002) only 5% of private land owners has written management plans for their forest properties, yet these 5% control 39% of privately owned forest land. Of the forest land with management plans 43% is controlled by the forest industry. Management planning, and data collection in support of management planning, is done in-house, by consultants or by state service foresters.

This study tour only made two stops in and around Seattle. Obviously this is inadequate to capture LiDAR activity in the United States.

United States Department of Agriculture Forest Service.

Stephen Reutebuch heads the Silviculture and Forest Models Team at the Pacific North West Research Station of the USFS. The original driver for the LiDAR work done by his team was the development of techniques to measure forest attributes relevant to fire management (topography, horizontal and vertical distribution of fuel load), not timber inventory. The project was successful and clearly demonstrated the suitability of the technology for the intended application, but also for timber inventory (after all timber is an excellent fuel). LiDAR as a data source for timber inventory does not incite much enthusiasm in the USFS possibly because timber production is no longer the main focus of forest management.

The USFS Forest Inventory and Analysis group thus far has shown little interest in the technology. This may change in the not too distant future now that Hans-Erik Andersen has joined the FIA team in Anchorage, Alaska and a University of Washington PhD candidate Yuzhen Li is working on a project “Integrating small footprint LIDAR data into forest inventory and analysis in Kenai Peninsula, Alaska”.

Weyerhaeuser.

Zhenkui Ma is in-house remote sensing consultant at Weyerhaeuser, a company with the critical mass (13.5 million ha of forest land, $22.6 billion sales) and expertise to develop and implement LiDAR solutions. It was therefore an obvious destination for this study tour. Zhenkui strongly endorsed airborne LiDAR as a tool for forest inventory ("100 % suitable", "eventually it will be a standard tool, like aerial photography today") suitable for measuring stand variables like height, mean diameter, basal area, volume. He said that LiDAR would suit Weyerhaeuser's circumstances in the USA because a large proportion of their resource consists of single species conifer plantation. He however stopped short of providing any specific details on the deployment of LiDAR in an operational context, as it is company policy not to publicise such details.

Canada

Of Canada's 979 million ha of land area, 310 million ha are classified as forest land. Unlike the other countries visited during this study tour the majority of Canadian forest land is in public ownership: only 6.2% is in the hands of non-industrial forest owners and just 1.3% in the hand of industrial owners. The provinces control 80.0% of forest land, the territories 11.8% and other public owners the remainder. Some 80% of wood production is derived from public land (Source CaNFI).

The Pacific Forestry Centre of the Canadian Forest Service has the mandate to compile provincial and territorial inventories into a National Forest Inventory

Under Canada's Constitution, the responsibility for managing the country's forests rests with the provinces and territories. The 10 provinces and 3 territories develop legislation, regulations and policies; allocate timber licences; collect stumpage fees and collect data. Laws, regulations and policies can differ from province to province but the forest management framework can be generalised as in Figure 2.

Forest inventories are conducted to assess the forest resources present on lands licensed to productive forestry. The inventory has a strategic focus. Inventory standards and methodology are specified by the provinces. Funding comes from the provinces but data collection work may be subcontracted. Based on the inventory results forest management agreements are drawn up and industry licences are issued to companies for periods of 25 to 99 years.

Often the forest inventory information is used by the companies to develop 20-year stand level management plans. However the provincial inventory has not been designed for this purpose. Companies may collect additional data for operational forest management planning. The companies submit 20, 5 and 1 year plans for approval to provincial authorities.

Figure 2: Forest management framework in Canada (Source: Canadian Forest Service, Ontario)

Enhanced Inventory Project – Forest Research Partnership, Ontario

The Forest Research Partnership is a joint undertaking between the Ontario Ministry of Natural Resources, the Canadian Ecology Centre, the Canadian Forest Service and Tembec Inc. It was created in 2000 and conducts research projects into enhanced forest productivity and sustainability.

One of these projects was the Enhanced Inventory Project, short for "Acquiring and testing Multiband Orthophotography (and integrated LiDAR) for Production of Enhanced Forest Inventories in the Great Lakes of St. Lawrence Forest." Web: http://enhancedinventory.ca This project complements and builds on the findings of a similar project in the boreal Romeo-Malette forest in the NE of Ontario province. Tembec Inc is the forest licence holder in these forests.

The main objective of the project is to test and evaluate new technology to develop an enhanced Forest Resource Inventory (eFRI) in replacement of the current aerial photography and ground sampling approach. The involvement of intended users of the eFRI (Ontario Ministry of Natural Resources and Tembec Inc) is a strength of the project. Operational deployment of new knowledge and technologies is part of the overall project design, increasing the chances of successful transition from a research to an operational implementation phase. For research and technical expertise the project drew on research institutions (QU, Paul Treitz' team; UQAM, Benoît St-Onge), the Canadian Forest Service (François Gougeon, Don Leckie) and companies such as M7-Visual-Intelligence (Digital imagery and LiDAR data collection), Lim Geomatics (LiDAR modelling and software development).

During the visit to the Canadian Ecology Centre Paul Courville provided an overview of the accomplishments of the project so far. These include digital terrain modelling for a number of applications, canopy surface modelling, assessment of stand variables by species (mean diameter, basal area, volume, biomass), stand level diameter distributions, and an increased understanding of the influence of LiDAR data collection variables on estimation of forest variables. For more information the reader is referred to a presentation available on the web by Ken Durst (Tembec) about the Romeo Malette project http://www.enhancedinventory.ca/publications/cdOct18/Presentations/Ken%20D.pdf
A presentation by Valerie Thomas provides the Queens University perspective http://forestresearch.ca/Oce_val.pdf .

The achievements of the project are remarkable because the forest-types in the project area are challenging due to their mixed species, and uneven-aged stand structure (see Figure 3).
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Figure 3: uneven-aged, mixed forest near Algonquin Provincial Park, Ontario with pine, maple, birch, fir, hemlock (and possibly other species)

Tembec Inc has taken LiDAR to an operational scale with the completion of the digital photo-LiDAR survey of the 640,000 ha of the Romeo-Malette forest. According to Ken Durst Tembec's analysis has shown that the expenditure of airborne data collection and processing can be regained within two years owing to significant cost savings per cubic metre harvested. A better DEM allows to build more effective road networks that cost less to build, minimise fuel consumption, optimise skidding, and avoid sensitive areas. The inventory information derived from LiDAR data is more suitable to meet modern forestry business needs than existing strategic inventory methods. It is suitable both for strategic and operational planning purposes.

Expectations are that LiDAR data will become cheaper (about C$0.50 per ha at a data density of 1 pulse per m^2). At this price the eFRI could be within the budgetary range of the Ontario Ministry of Natural Resources. The research by the QU team shows that even at low density and high flying altitude very useful information can be collected from LiDAR data (Chasmer, 2006). The price could therefore drop even further

Elsewhere in Canada

The Tembec Inc enhanced inventory is the main example of operational use of LiDAR in forestry encountered in Canada during this study tour. But there appear to be other projects in the pipeline that have a high probability of eventuating:

- Nicholas Coops mentioned discussions with provincial authorities in Alberta about a project to use LiDAR to assist building of harvesting roads. The objective is to pre-emptively harvest forest vulnerable to attack by pine beetle so as to slow down the spread of this pest. LiDAR is favoured because Digital Elevation Models can be produced quicker and more accurately than with photogrammetric methods.
- Benoît St-Onge mentioned several initiatives in the province of Québec:
    - Hydro-Québec, the main publicly owned electricity utility, is planning to fund a research chair at the University of Montreal to develop systems to manage trees near powerlines. Airborne LiDAR would be used to measure individual trees and individual tree growth models will be developed to model the growth of these trees. Better management of trees near powerlines could save Hydro-Québec millions of dollars.
    - A commission to study public forest management in Québec began its activities in 2004 and found serious deficiencies in the methods used to assess the state of the forests and to evaluate the maximum sustained yield. The so-called "Coulombe Commission" recommended the appointment of a Chief Forester responsible, inter alia, for reviewing methods for forest assessment - LiDAR will be considered as one of the alternatives.
    - The Natural Resources Ministry of Quebec has agreed to conduct a resource inventory over 180,000 ha based on LiDAR and digital imagery and applying the individual tree analytical techniques (ITC) developed by François Gougeon of the Canadian Forest Service.
    - Packaging multi-national company Smurfit-Stone is the largest private forest land owner in Québec (400,000 ha) and is planning to collect LiDAR and high resolution digital imagery over its entire resource.

Norway

The productive forest area in Norway is approximately 7 million ha. About 80% of this is owned by a large number (120,000) of non-industrial private forest holders, 4% by private forest industry and the remainder by State and community owners (Eid, 2006).

Norway has a National Forest Inventory Program with a history going back to the early 1920s. Its implementation is the responsibility of the Norwegian Forest and Landscape Institute. Its main data source is the measurement of field plots.

The Ministry of Agriculture and Food provides regulations for forest planning (content and quality). Forest Planning is a requirement for certification: without certification timber cannot be traded. Forest plans are mostly produced for areas of 5000-10,000 ha comprising of many properties. State subsidies are available provided 80% of the forest owners in the area participate. Forest Plans focus on timber production as well as environmental management. Mandatory data collection is related to these objectives. The planning cycle is approximately 10 years. Annual areas covered are 300,000-500,000 ha.

Forest planning is initiated by County councils who set up a steering committee (forest owners are strongly represented) that will develop specifications for the planning project.

Forest planning is carried out by specialised service companies that compete for projects. The company making the best offer (content, accuracy, price) wins the contract.

Mandatory information requirements for planning are collected at the stand level and include height, volume, age, species mix, site quality, stocking (young forest), recommended treatment and bio-diversity metrics (eg dead trees, % broadleaved species,…). Methods applied conventionally rely strongly on aerial photogrammetry. Aerial photos are used to delineate stands and carry out a stand inventory (species proportions, height, volume, age, site quality). Field visits may be carried out to verify the aerial photo interpretations. Some projects include a systematic field inventory to calibrate photo interpretations but since this requirement is optional this is the exception rather than the rule.

Owing to the research by the team of Erik Næsset (Næsset, 2004), laser-based inventory has become a practical and economic alternative in Norway. The laser inventory consists of several steps:

- stand delineation and stratification (species, site quality, age class) based on aerial photography.
- Stand assessment (height, mean diameter, basal area, stocking, volume) based on airborne LiDAR and field sampling.

According to Næsset Norway forest ownership structure, government regulations, a long history of using remote sensing (aerial photography) for inventory and the outsourcing of inventory to competing service companies conspired to create a positive environment for the development and acceptance of laser based forest inventory. It now enjoys a rapidly increasing market share of more than 10%. All Norwegian forest inventory service companies are developing laser inventory capabilities. However, the company with the longest track record is Prevista, based in Kongsberg.

Prevista

Prevista was founded in 2001 through the merger of several companies thus becoming the largest forestry and land-use planning service company in Norway. Prevista has developed an operational laser inventory modelled on Næsset's two stage method. Prevista usually provides a complete service including field and LiDAR data collection (which is sub-contracted). Products (forest stand maps, resource statistics, management plans) are delivered via the internet to customers. Product development is still continuing. Recently the company delivered diameter distributions as part of the stand inventory for the first time.

Prevista has developed a suite of systems to support production activities. Productivity gains are made by combining digital imagery and LiDAR. For example a system was developed whereby LiDAR tree height data can be viewed on top of digital photo imagery to assist stand stratification based on productivity. This accelerates photo-interpretation by 20%. Another application merges LiDAR and Ikonos data sets and uses object-oriented image processing package eCognition to delineate and classify stands and detect harvesting operations. The company has developed software to manage and process LiDAR data.

Thomas Brethvad, Director of the Forest Division, said that one in two projects won by Prevista now has a laser inventory component. LiDAR inventory is typically confined to the productive portion of the project area. Prevista's customers are in Norway and Sweden. All inclusive prices are 60-80 NOK per hectare.

Sweden

The total forest area of Sweden is 28.5 million ha of which 22.9 million ha is classified as productive. About 51% of the productive forest area is in the hands of 350,000 owners spread over 250,000 forest holdings. Many owners are organised in one of 4 large Forest Owners Associations which provide support in harvesting, inventory, silviculture but may also be the owners of pulp and/or saw mills. About 24% of forest land is owned by 3 large and 4 smaller private companies. 25% of forest is owned by State and community bodies.

The Swedish National Forest Inventory is carried out by the Department of Forest Resource Management of the Swedish University of Agricultural Sciences (SLU). It has a history going back to 1923. Source data is collected in systematically-located field plots.

It is currently not mandatory for private forest owners to have conventional forest management plans. Since 2003 however the Forest Act prescribes a Forest and Environment Declaration which translates in an obligation to at least collect some data and prepare a simple forest management plan. In Sweden forest inventory and management planning is not subsidised by the government. Some of the Forest Owners Associations have introduced additional requirements (so-called "Green Forest Management Plans", "Eco Plans") which are adequate to achieve FSC or PEFC certification. These plans usually have a planning horizon of 10 years. Large companies use the Forest Management Planning Package developed by SLU. This is a strategic planning system that relies on objective field inventory of a subset of stands. The next generation of this system is currently being developed at SLU under the Heureka research programme.

The application of LiDAR has mostly been considered in the context of tactical and operational planning. Tactical planning requires stand level data. Stands are usually delineated using aerial photography and stand variables are sometimes estimated using objective sampling methods, but more frequently they are subjectively estimated based on a visual assessment or arbitrarily placed point plots (angle sweep). The production of a Management Plan using conventional techniques costs about SEK100 (A$18).

Planning is carried out by Forest Owner Associations, the Swedish Forest Agency, private companies or specialised service providers. Most large companies would prefer to contract out their resource inventory. According to Professor Håkan Olsson of SLU forest companies are very cost-conscious and any alternative inventory methods would have to be lower cost for the same quality of information. There is little willingness to pay extra for better information.

Airborne LiDAR research commenced in the early nineties, with early publications by Mats Nilsson in 1996. The first operational LiDAR-based forest inventory was conducted in 2004 over an area of 5,000 ha. The methodology applied was very similar to that developed by Næsset in Norway. This project was written up by Johan Holmgren and Thomas Jonsson and can be accessed at http://www.isprs.org/commission8/workshop_laser_forest/HOLMGREN.pdf . At the time (2003) the cost of 1 pulse per m^2 LiDAR data came to SEK30 /ha (A$5.3) but Johan Holmgren estimates that today the price would be half of that.

The most likely users of LiDAR-based techniques are the large companies that own 50% of Swedish forests. For small private forest holdings adoption is dependent on a business model that allows cost-sharing and/or on government policy (Olsson).

With the formation of FORAN Remote Sensing in 2007 Sweden now also has a LiDAR-based forest inventory service provider. FORAN Remote Sensing is a subsidiary of Norwegian forestry and nature consulting company FORAN which is active in Norway, Sweden and Latvia. What sets it apart is that it uses high density LiDAR data sets (10 pulses per m^2) and a proprietary methodology to produce information at the individual tree level (position and dimensions of single trees) as well as stand variable estimates derived from individual tree data. Instrumental to the development of this capability was the recruitment of laser expertise from an R&D department within Swedish Defence.

According to Production Manager Tobias Jonmeister, FORAN now has firm contracts for an area of 350,000 ha (with projections of 500,000 ha by the end of the year). Customers are forest companies looking to update forest management plans but also power line and railway companies, and, interestingly timber processing or harvesting companies that don't necessarily own any forest land but have a stake in knowing where the wood is. Price range of all inclusive forest inventory is SEK 70-130 (A$ 12-23) per hectare. End-products are delivered as spatial data sets ready for integration in GIS and management systems.

Jonmeister explained that the reasons why customers opt for individual tree laser inventory rather than conventional methods include better accuracy and 100% sample; better stand delineation and option to use dynamic rather than static stand boundaries; new information such as diameter distribution by species and data on environmentally important trees/stands; realistic visualisation of forest and landscape. He suggests that

the information provided will only gain in usefulness when integrated with on-board computers and GPS in harvesting machines.
The success of FORAN Remote Sensing LiDAR services is remarkable, given the short period they have been available. The Swedish industry appears to be ready to embrace LiDAR-based approaches. Unfortunately the author was unaware of FORAN before undertaking this study tour because otherwise a visit would definitely have been included in the itinerary to see the SingleTree® process in operation.

Finland

The total forest land area in Finland is 26.3 million ha. About 52% of this is owned by non-industrial private forest holders, 8% by private forest industry, 35% is State Forest and 5% is other public forest. There are 440,000 private forest owners and average holdings are 30 hectares. Private forest owners are organised in Forest Management Associations that may be active in timber marketing, harvesting contracting, supply of seedlings, planting. 80-90% of wood supply to industry originates in privately owned forest. Annual timber volume increment exceeds harvest (Finnish Statistical Yearbook, 2006).

METLA is responsible for the implementation of the Finnish National Forest Inventory which started in 1922 and is currently in its 10th iteration. Its key data source is field sampling.

Forest inventory for management planning is carried out by different agencies depending on who owns the forest.

The 13 Forest Centres under the Ministry of Agriculture and Forestry have a statutory role in regional forest data collection and forest planning of non-industrial forest properties. They also enforce the Forestry Act. An annual budget of €18.5 million is allocated to the inventory of family-owned forest. This data is used for regional planning/monitoring but also to develop forest management plans in consultation with owners. Forest owners are not obliged to purchase these management plans. Forest inventory and management plans are updated every 10-20 years. The Forest Centres set inventory guidelines but are guided by the Forest Development Centre (TAPIO). Current methods are stand (compartment) based and are usually labelled subjective because assessor judgement plays an important role in stand delineation and no formal statistical system underpins number and location of relascope plot measurements. Cost per ha is €18.5/ha with the cost of field inventory alone accounting for €8-9/ha.

Private industrial and state forest companies make their own arrangements for forest planning and data collection but use comparable methods and information systems developed and maintained by METLA.

State owned forests are assessed by the Finnish Forest and Park Service (Metsähallitus).

To improve the efficiency of stand level inventory techniques Finland is pursuing two complementary strategies: (1) alternative data collection methods such as laser scanning and (2) computational updating of inventory data through simulation of growth and yield.

Government-driven LiDAR initiatives in Finland

According to Juha Hyyppä the National Land Survey of Finland will commence LiDAR data collection towards the production of a National Digital Terrain Model in 2008. The data will be flown at 0.5 pulses per m^2, which would be adequate for some forestry applications. Some of the data is likely to be made available to other government agencies.

Juha Hyyppä, Matti Maltamo, Timo Tokola, Kari Korhonen all talked about the impending changes in forest inventory practice in Finland. Juho Heikillä provided a powerpoint presentation and also referred to an information brief at www.forest.fi . In essence the Ministry of Agriculture and Forestry has gone through a review process of forest inventory approaches for private family forest and has decided that from 2010 onwards :

- all forest inventory conducted by the Forest Centres will be based on laser scanning, aerial photography and deliberately positioned field plots. Non-parametric plot based methods will be applied to generate estimates by forest stand by species of age, height, diameter and volume.
- measures will be introduced to increase the amount of reporting of forest management activities such as planting, tending, harvesting, etc. This information will be entered in forest resource data bases and used to model forest statistics in between successive inventories. A next generation forest planning system named Simo is being designed by a team including Timo Tokola (University of Joensuu) and Annika Kangas (University of Helsinki).

The perceived benefits are:

- estimated cost savings of 35-40%
- field measurement time reduced by 75-80%. This frees up time for planners to concentrate more on communicating and advising forest owners so that management plans will better meet owners' expectations and be better understood by them.
- more accurate and more up-to-date resource data.

Arbonaut Oy

There is also activity in the private industrial scale forest companies. Forest information service company Arbonaut Oy is assisting private company UPM (900,000ha) to implement LiDAR and aerial photography based inventory solutions.

Manager, Remote Sensing, Vesa Leppanen described the typical service Arbonaut Oy would provide:

- guidelines for field sampling including manuals,
- specifications for LiDAR and aerial photography data capture,
- data processing using proprietary ArboLiDAR software,
- delivery of stand attribute estimates as spatial data set,
- delivery of accuracy statistics.

Arbonaut Oy do not get involved in data collection. Minimum project size is about 30-40,000 hectare. For such a project area approximately 500 field plots are needed (costs ±€ 25,000 or less than € 1 per hectare). Price quoted by Arbonaut is € 4 per hectare, all inclusive. Adding LiDAR and aerial photography costs it would appear that this inventory solution costs less than € 10 per hectare.

Another company involved in pre-operational LiDAR forestry work is Blom Kartta (formerly FM Kartta). This company has a 60% share of the Finnish market for air photo-based geographic information data. It forms part of the Blom Group which recently won the contract to produce the Danish National Digital Terrain Model using LiDAR.

According to Juho Heikillä companies such as Arbonaut Oy and Blom Kartta will act as contractors to the Forestry Centres for data processing. Forestry Centres will remain responsible for field data collection and planning.

Research and development

Introduction

There are two fairly distinct methods for extracting forest information from airborne LiDAR data: plot based and individual tree methods.

Plot-based methods typically involve two stages. In the first stage relationships are developed between forest and LiDAR variables at the scale of a field plot. LiDAR variables are derived from the observed distribution of LiDAR heights in the plot. In the second (application) stage these relationships are applied to predict forest attributes all over the forest, using the LiDAR data as predictor variables.

Individual tree methods analyse the LiDAR point cloud (often fused with digital imagery) to detect, delineate (segment) and directly measure the attributes (species, height, crown diameter) of individual trees. Field data may be collected for bias correction purposes but the ultimate objective is to improve methods to the point where field data collection becomes unnecessary.

Each method has different strengths, weaknesses and future potential and this in turn inspires the research.

This overview of research and development only refers to recent work (2006 and 2007) and only to the institutions visited. It is not a literature review.

Plot-based methods

The strength of plot-based methods lies in their robustness, relative simplicity, lower computational requirements and proven ability to generate unbiased estimates of a wide range of stand level forest variables of economic and ecological significance including stocking, basal area, volume, biomass, mean diameter, leaf area index, crown cover, canopy depth, etc.

New research focuses on methodology and finding the optimum levels of inputs - LiDAR and field data. Researchers are also trying to develop new applications.

Non-parametric prediction method

Regression analysis is the approach most often used to relate dependent forest variables to predictor LiDAR variables in stage 1 of the plot-based method. However in Finland Maltamo and colleagues obtained better results using a non-parametric method (Maltamo et al, 2006b). The technique used was a variant of the k-MSN approach (k Most Similar Neighbour) whereby similarity was calculated based on canonical correlation. Independent variables used as predictors included LiDAR, aerial photography and site class variables. As mentioned earlier a non-parametric approach has been selected for operational implementation of laser-based inventory in 2010 all over Finland. Arbonaut Oy has implemented the method in its ArboLiDAR software.

Optimising LiDAR data collection.

An understanding of the relationship between data collection parameters and quality of the information produced is important to work out the combination of data collection parameters that will produce the required level of accuracy at minimum cost. Trying to get these parameters right is very important according to Juha Hyyppä. If parameters are changed from one campaign to the next this can jeopardise the suitability of the data sets for change assessment.

Recent work by Laura Chasmer (Chasmer et al, 2006) and Valerie Thomas (Thomas et al, 2006) at QU, Nick Goodwin (Goodwin et al, 2006) at UBC has made significant contributions to this area of research. It examined how data density, flying altitude and pulse repetition rates affect the precision of forest variable estimates. Results indicate that even collected at high altitude, low density LiDAR data provides very useful information for forest management. But the research also shows that a change in LiDAR data collection parameters can change the relationships between LiDAR and forest variables, and therefore the calibration of prediction models.

Optimising field data collection.

The collection of field data in reference plots to calibrate relationships between LiDAR and forest variables is a necessary expenditure in the plot-based approach. What is less understood is how much field data should be collected, where plots should be located, how large plots should be. Another important question is under which circumstances calibration models could be “transferable” from one area to another. Answers to these questions will lead to operational optimisation and cost reduction. Several researchers are working on it.

At UMB Liviu Ene has studied alternative sampling strategies starting from a simulated forest and simulated LiDAR data sets as part of a postgraduate research project. The results of these simulations can assist in the design of field trials. He is now taking this work to the next level as a PhD candidate. Johan Holmgren and Kenneth Olofsson at SLU are using simulation techniques to explore effect of plot sampling designs on model development. At UJ Aki Suvanto is working on the transferability of laser calibration models as well as the impact of reference plot locations on the calibrations. A recent publication by Matti Maltamo reported that truncated Bitterlich point plots can also be used in the calibration process (Maltamo, 2007).

Another piece of work related to transferability of LiDAR calibration models is by QU guest lecturer Chris Hopkinson (Hopkinson, 2006). He investigated 13 LiDAR datasets captured over 13 vegetation types on 5 sites all over Canada between 2000 and 2005 using 4 different scanners and developed a simple linear predictor model for mean canopy height that worked reasonably well across all forest types. The LiDAR variable used was the standard deviation of all first and last return laser heights, named L_{SD}.

Generating diameter distribution information.

The first to derive diameter distributions using plot-based methods were Gobakken and Næsset, and more recently Bollandsås and Næsset (Bollandsås, 2007). Their techniques have been applied by Prevista to provide diameter distribution information to customers. Success was also achieved by Maltamo. Johannes Breidenbach has developed diameter distributions for mixed German forest (to be published). Paul Courville showed diameter distributions produced by the Enhanced Inventory project.

Generating diameter distributions is a significant achievement because coupled with height distributions and taper models they make product and assortment prediction possible.

Information by species.

Virtually all the researchers met during this study-tour conduct research in mixed species forest. Inventories need to produce resource information by species. This creates a particular challenge in the plot-based method that in all probability cannot be solved with low density LiDAR data alone. Prevista, adopting an approach by Næsset, minimise the problem by using aerial photography to stratify stands based on dominant species, age and productivity. They then proceed to calibrate separate prediction models for each stratum.

In recent research Petteri Packalén from UJ compared two techniques to assign volumes to species using aerial photography and LiDAR data: a two-stage approach whereby total volume is apportioned to species based on fuzzy classification of aerial photographs and a one-stage approach using k-nearest neighbour techniques with direct volume estimation by species (Packalén et al, 2006).

Vesa Leppanen explained that the proprietary system developed by Arbonaut apportions volume based on the ratio of the aerial photo pixels classified to each species.

Measuring canopy structure.

The horizontal and vertical structure and composition of forest canopies are relevant to those interested in bio-diversity, habitats, physiology, forest productivity, process-based growth modelling, wood quality, fire behaviour, to name a few. Existing techniques for measuring canopy attributes are expensive. Many researchers have demonstrated that LiDAR data represent a rich source of information on canopy structure.

Nicholas Coops and colleagues have recently added to this evidence studying the relationship between field-measured tree height, crown dimensions, cover and vertical foliage distributions and models of foliage distributions based on small-footprint LiDAR data in Douglas fir and Western hemlock stands on the east coast of Vancouver island (Coops et al, 2006).

In Finland Matti Maltamo and colleagues compared detailed field measurements of crown height to LiDAR predictions of the same and found that LiDAR-based approaches produced equally good if not better results. In Finland crown height and mean tree height is used as an indicator of quality and value of the growing stock (Maltamo et al, 2006).

Valerie Thomas found LiDAR to provide useful structural canopy information to help quantify the fraction of photosynthetically active radiation absorbed by the canopy (Thomas et al, 2006). She also studied correlations between LiDAR variables and measured concentration of chlorophyll a+b. (Thomas et al, 2007).

In a project funded by the Research Council of Norway researchers from Næsset and Maltamo's teams are exploring how high density LiDAR data can be used to predict stem quality of Scots pine, presumably by studying variables related to branching habit.

Johan Holmgren talked about a project in the context of the National Inventory of Landscapes in Sweden using LiDAR to assess the shrub cover both under and without forest cover. The shrub layer provides food and shelter to wildlife.

At UBC Nick Goodwin is working on detecting natural regeneration under tree canopy. Knowledge about the presence or absence of such regeneration can steer management towards clearfell or shelterwood techniques.

Also at UBC Chris Bater is investigating to what extent LiDAR can be used to assess 11 sustainability indicators required by the British Columbia Ministry of Forestry for monitoring purposes.

Erik Næsset intends to use LiDAR data to track movement – if any - of the mountain and arctic tree line as a consequence of climate change.

Individual tree methods

Individual tree methods generate information at the individual tree level. Tree coordinates, height and crown diameter are directly derived from the LiDAR and optical imagery data. Tree diameter and volume are predicted using allometric relationships.

Under some circumstances information at the individual tree level can be very useful. Information about the location and attributes of specific trees can be useful in shelterwood, continuous forest cover, minimum-diameter limit silvicultural systems (Malaysia, Indonesia), or if reduced impact logging is practised. Some forestry organisations use individual tree growth models in planning systems. Individual tree information can be used to predict product outturn.

Individual tree methods offer advantages when species diversity is high and information by species is required. But automated species recognition methods need to be perfected.

In theory individual tree methods do not require field data collection. However, the problem of detecting trees overshadowed or suppressed by other trees, or of separating trees with interlocking flat crowns, such as the sugar maples in Canada (Benoît St-Onge), has not been resolved yet. Field data collection will remain necessary to measure variables that cannot be measured from the air and to manage the discrepancies between laser and field measurements, which are data and algorithm dependent (Olsson).

Individual tree methods require higher data densities than plot based methods (Juha Hyyppä: 2 pulses per m^2; Juho Heikillä: 4-5 pulses per m^2).

Most institutions visited during this study tour conduct individual tree related research projects. Erik Næsset is in the process of starting up a large EU funded project, with participation from several European countries, to progress individual tree methods *and* carry out large scale validation.

Better algorithms

Juha Hyyppä talked about the International ISPRS/EuroSDR Tree Extraction Comparison trial whereby 10 or so European and North American research institutions were asked to apply their in-house developed algorithms to the same high-quality test data set. The results of the trial showed that the tested algorithms produced highly variable success rates, to the point where Hyyppä concludes that algorithms are as important as pulse density. The trial results will be published.

Hyyppä's team is still working on algorithm development and considers that success rates of discovering the missing trees can be significantly improved. One of the keys is careful filtering of the digital surface model. The team is also studying the gradual merging of tree crowns as LiDAR pulse density decreases. Hyyppä argues that merged crowns should not necessarily be a problem provided reference field data is available to develop relationships between crown clusters and corresponding tree variables. Note that such an approach starts to blur the distinction between individual and plot-based approaches.

The LiDAR group headed by Johan Holmgren is active in an interesting cooperation project between SLU and the Forest Research Institute at Uppsala. He described the approach under development as imputation of harvester data. The idea is to relate the airborne "signature" of a tree to the harvester measurement of the same tree, to do this for a large number of trees of a range of sites, sizes and heights and to store the data in an imputation data base. It then becomes possible, given the airborne signature of a tree, to locate the most similar signature in the data base and to impute the harvester data to the tree under assessment. The data imputed will be actual product assortments. The method exploits the capabilities of modern harvesters to capture data on location, stem diameter, quality and product outturn of every tree processed. It is grounded in field measurements, but field measurements made by a machine!

At UJ at least two PhD candidates are working on individual tree methods. Jussi Peuhkurinen (UJ) compared LiDAR-based (plot and individual tree) and conventional inventory techniques (systematic plot inventory and "compartment inventory") and tested results against the harvester data obtained from two pure Norway spruce stands. Individual tree LiDAR techniques were found to produce best results for diameter distribution and assortment prediction. The individual tree approach was able to describe the bi-modal diameter distribution occurring in these thinned clear-fell age stands. The work will be published in Forest Science shortly.

Species identification

Automated species identification at the individual tree level remains a challenge even if aerial imagery as well as LiDAR data is available.

The work by Ilkka Korpela and Timo Tokola shows that failure to identify species accurately is an important source of error in imagery-based stand volume estimation (Korpela and Tokola, 2006).

In 2004 Holmgren and Persson demonstrated that high density LiDAR data can be used to differentiate tree species based on crown shape difference. At UJ post-graduate student Jari Vauhkonen (supervised by Tokola) is getting promising results identifying species with an "Alpha shape"-based approach applied to high density laser data. His technique successfully detected and identified 98% of trees in the stand. The approach is now being tested on other stands. The work is not yet published.

At University of Washington PhD candidate Sooyoung Kim is working on species classification with leaf-on, leaf-off data, using LiDAR intensity and crown shape variables coupled with unsupervised clustering techniques.

Methods based on high resolution aerial imagery backed by LiDAR

There appears to be a general consensus that compared to aerial photography LiDAR is the more powerful data source for constructing digital elevation models, especially under dense forest.

Benoît St-Onge (UQAM) envisages significant advantages in using aerial imagery and digital photogrammetric techniques to construct digital surface (canopy) models. Advantages include the lower price of aerial photography and the availability of historical photos. He also argues that the possibilities offered by aerial imagery will significantly increase because:

- capabilities of digital cameras will continue to improve (multiscopic imagery, i.e. multiple images of the same target taken from different angles)
- imagery registration/orientation will be automated owing to better GPS and navigation systems
- better software will become available to automate object matching on multiscopic imagery.

His idea was to develop a method whereby the terrain is modelled using LiDAR data and the canopy surface is modelled using aerial imagery. The key is accurate 3D co-registration of aerial imagery and LiDAR data.

In a recent experiment (to be published shortly) he reconstructed the growth of trees using a LiDAR DEM and a series of aerial photos taken over time. Trees at the trial site were first geo-referenced using total stations. Next they were felled and stem and growth ring analysis was carried out to reconstruct tree growth. Actual tree height growth was then compared to that predicted from aerial photography. The technique could be used to assess site index and growth rates.

With his hybrid method Benoît St-Onge provides an alternative vision to the LiDAR-centric vision prevailing in this report. The competition of alternative visions can only benefit the end-user.

LiDAR for large area inventory

Each of the countries visited has a well-established and well-funded National Forest Inventory program. Is there a role for LiDAR in NFI s?

Mike Wulder of the PFC is interested in the problems associated with integrating resource information over a range of spatial scales. In view of the vastness of Canada Wulder does not consider LiDAR to be a suitable tool for wide-area NFI assessments. However he sees several possible applications for LiDAR in the context of the Canadian NFI:

- using LiDAR data to validate the interpretation of the 2 by 2 km NFI photo plots established on a 20x20 km grid all over Canada.
- To update photo plot polygon information. The periodicity of updates would be a function of forest rates of change.
- Using LiDAR in profiling mode to assist the interpretation of satellite imagery. (Wulder et al, 2007).

Næsset mentioned a collaboration project between UMB, NASA, SLU and Yale University looking at using LiDAR in scanning mode as a sampling tool i.e. strip sampling for regional forest inventory, and comparing scanning LiDAR with profiling LiDAR (Nelson, R. et al, 2007) for regional inventory. This effort is based on ground calibration with conventional – but accurately located – National Forest Inventory Plots. The target area covers a Norwegian "NFI unit" of 27,000 km^2.

In Finland too researchers from UJ and METLA are exploring combining National Forest Inventory field plot data with LiDAR data to develop predictors that could be applied wherever LiDAR data is available, to generate forest information at a finer scale than the NFI plots alone would permit.

Hardware

The capabilities of airborne laser scanning systems are a function of the capabilities of the three sub-systems - laser scanner, Global Positioning System and Inertial Navigation System - and the computer system integrating these subsystems and data flows.

LiDAR system specifications have been improving rapidly over the years. Pulse repetition rates of commercial off-the-shelf systems have increased from 5,000 in 1995, 25,000 in 1999, 100,000 end 2005 to 167,000 beginning 2007 (Flood, 2001; Optech website). At the same time lasers have become more powerful so that for the same pulse repetition rate the energy of individual pulses has increased (Chasmer et al, 2006). Since scanner rates have also kept pace it follows that airplanes can be flown higher without losing return signal power or point density, so that wider swaths of terrain can be covered in one flight line. Given that the price of state-of-the-art LiDAR systems has remained about the same (approximately $1 million) it follows that data collection costs are decreasing.

Some LiDAR systems (for instance those manufactured by Riegl) supply full waveform data. This means that all the information of the returning pulse signal is digitised and stored. Most commercial systems only store 4 or 5 discrete points of the energy wave and discard the rest of the data. Researchers are only now starting to work with this type of data and the first challenge will be to deal with the much larger data volumes and processing requirements.

LiDAR system capabilities will continue to increase but another evolution that could generate even greater benefits could be the closer integration of different types of sensors (digital cameras, hyper-spectral) with the LiDAR unit. This however would impose more weather (cloud-free) and timing (sun-angle, leaf-on versus leaf-off) constraints, and also assumes that optimal flight parameters for the various instruments are compatible. Benoît St-Onge suggests that a lot of very expensive equipment could be sitting idle on the runway for much of the time.

Most LiDAR hardware is still designed for terrain surveying applications. Johan Holmgren asks the interesting question “what would a LiDAR system optimised for forestry look like?”

Software

LiDAR data sets can be very large and data processing can get fairly involved. Software and data bases must be designed accordingly. Several commercial software packages exist that perform generic tasks like LiDAR data classification, surface fitting, image processing (see table below). However specialised forest information extraction requires specialised functionality that as yet is not available in commercial software packages.

Service companies such as Prevista, Arbonaut, FORAN have developed in-house software systems. They are usually built around a certain methodology and are usually not commercially available because they constitute a real competitive advantage for the companies concerned.

Most forestry researchers use commercial software as well as applications developed in-house to process data and achieve research objectives. These tools get the job done but do not necessarily make for effective production systems.

Bob McGaughey of the US Forest Service, based at the University of Washington, has gone further than most in developing a suite of useful tools that is publicly available. The Fusion and LIDAR Data Viewer packages were developed to assist the Pacific Northwest Research station’s LiDAR research but have grown into a system with broader appeal.

Fusion and LDV provides both low and high level functionality. Functionality is accessed either through a suite of command line utilities (LiDAR Toolkit) or interactively through a GUI.

The command line utilities provide core capabilities such as data conversion, data import, indexing, validation, bare-earth point filtering, surface fitting (ground and crown), generation of images based on LiDAR intensity data. Tools are provided to excise small data subsets (i.e. corresponding to field plot boundaries). A tool aptly named Cloudmetrics computes a range of height distribution statistics for a submitted point cloud (i.e. max, min, standard deviation, percentiles,…). Commands can be written to batch files and run sequentially providing a powerful tool for developing repeatable processing flows. This is a highly desirable feature in a production tool.

The functionality for visually exploring the point clouds and surfaces is quite powerful. Aerial or satellite imagery can be loaded and simultaneously shown as a background. It is possible to focus on a particular 3D zone of interest, for example a cylinder centred around a tree, and to make interactive measurements within that zone.

Some of the functionality was designed with a plot-based approach in mind. Thus far Fusion does not provide all the tools needed to implement the application stage of the plot-based method. Over the next 6-12 months this may change as tools are being developed to allow the user (i) to specify models (LiDAR metrics and model form), (ii) to apply these models to the cells of a gridded area and (iii) to compile the results into an overlay.

Fusion is publicly available courtesy of the United States tax payer.

Software, example data set, manual: http://forsys.cfr.washington.edu/fusion.html
LiDAR overview and FUSION Tutorial: http://www.fs.fed.us/eng/rsac

At the Pacific Forestry Centre François Gougeon talked about the ITC (Individual Tree Crown) system which currently is implemented as an add-on to image analysis software package PCI. ITC is the result of 20 years of research into developing methods for identifying and delineating (segmenting) tree crowns on aerial photography. It can also be applied to images derived from LiDAR canopy height models or to fused photo and LiDAR images. According to Gougeon ITC is currently being developed as a stand alone application to be made available as commercial software.

Prevista have developed several software solutions to support digital aerial photography interpretation (stand delineation and stratification), to process LiDAR data, to package information in spatial coverages for electronic distribution to customers. The overall system supports a methodology as described in Næsset, 2004. Various parts of this IT infrastructure were demonstrated during the visit. A keynote address by Næsset at the 2005 Silviscan meeting shows some screenshots of software as well as an overview of the method (see http://cears.fw.vt.edu/silviscan/presentations/Author65.pdf)

Arbonaut have developed a production system named ArboLiDAR. This system implements all the steps of a non-parametric variant of the plot based approach (see above). It outputs results as spatial coverages that can be uploaded in most GIS. Routines are available to compute accuracy statistics of the information provided. This system is not commercially available.

UMB has developed a software kit where both the area-based method (Næsset 2004) and the single-tree method were implemented. The area-based part of it will be used in regional inventories.

Both Paul Treitz and Juha Hyyppä mentioned they are involved in LiDAR software development.

To close this section a list is provided of software used or mentioned by the people met during this study tour.

Table 1: LiDAR processing software

Software	Details
Fusion/LDV	See above
ITC	Individual Tree Crown system (see above)
Terrascan, Terramodeler, Terramatch TerraPhoto	Market leading suite of LiDAR data classification and modelling software.
Cloudpeak	Surface Magic: automated bare earth extraction; ASPRS LAS in and export; visualising LiDAR data sets, limited functionality version of LASEdit is free.
LiDAR analyst	by Visual Learning Systems; add-on to Arc GIS or ERDAS; provides some functionality for feature recognition including trees; trial version available.
ERDAS Imagine	Used by some for purpose of tree identification, segmentation
Arc GIS	Spatial analyst, 3D Analyst extensions provide tools for surface fitting, gridding and many more. ArcGIS 9.2 provides extensions for storage of LiDAR data in LAS format
PCI	Offers a LiDAR toolbox
TreeVaW	Tree Variable Window tree canopy height model processing software by Sorin Popescu. Runs under IDL. Free on request http://www-ssl.tamu.edu/personnel/s_popescu/TreeVaW/
ET Geowizards	Extension to Arc View or ArcGIS, provides some 100 GIS functions operating on points, lines, polygons; to generate surfaces etc. About 80 of these functions are free.
Geocue	Suite of products including Geocue, LiDAR1, DEM Cuepac, Pointvue LE, LAS reader. Pointvue LE is a 3D Lidar visualisation tool that can be downloaded for free. LAS reader is a ArcGIS 9 plug-in to read LAS format data files. Free to download.
Taudem	Terrain analysis using digital elevation models – hydrological focus; toolbar plugin to ArcGIS 9.0 or MapWindow. Freeware.
LP360	Extension to Arc GIS; reads LAS data files and creates ArcMap data layer; conversion ASCI files to LAS data format; download trial version 30 days
QT modeller – Applied Imagery	Importing, visualisation, editing, surface fitting. Two products: Quick Terrain Modeller and Quick Terrain Reader.
ENVI	Data visualisation and image analysis, feature extraction module under development
eCognition	Object based image analysis; used by University of Salzburg to develop tree segmentation solutions

Relevance to Australian Forestry

Technical feasibility and information requirements

The examples of operational LiDAR applications discussed in previous paragraphs routinely produce information such as Digital Elevation Models, stand maps, estimates of stand parameters such as stocking, mean diameter, basal area, volume, estimates of these variables by species. Some companies have started supplying diameter distribution information. One company provides information at the individual tree level. In the countries where these applications were deployed LiDAR outcomes were usually superior to outcomes of conventional methods, both in terms of precision and information content.

Many of the applications which have been operationally deployed overseas have been successfully demonstrated at a research scale in Australia (a discussion of Australian research results is outside the scope of this report but a good review can be found in Russell, 2007). As a general rule LiDAR applications become more technically feasible as the complexity of the terrain, forest structure and species composition decreases. In Australian even-aged, single-species plantation forest the technical challenge of extracting a comparable piece of information, say volume per hectare, should be smaller than in the mixed species, mixed structure forests of Canada and Scandinavia.

It is less clear whether LiDAR-based inventory can match the capabilities of existing Australian forest inventory systems. LiDAR-based techniques are undoubtedly adequate to meet information requirements of forest growers that do not have to worry about product differentiation, for example as in short-rotation plantation forestry for pulp wood production. However, LiDAR-based inventory has not yet been shown to be able to provide the product assortment information that forest growers who market products differentiated based on quality and size have come to rely upon. Some of the Australian inventory systems have a very strong focus on product quality and go as far as to map products in individual stems. Internal and external stem defects are important in native forest but also in radiata pine plantations.

Cost/benefit analysis

In Australia individual forest owners, whether they are private or public, industrial or non-industrial size, have a large degree of autonomy in deciding how to collect forest resource information. The decision to introduce a new technology will be based on an internal cost/benefit analysis.

The following are some of the benefits associated with LiDAR-based solutions, as related by those interviewed during this study tour:

- reduced harvesting costs owing to better topographic and stream network maps, better stand delineation and inventory.
- information that is useful for strategic as well as operational planning.
- Improved accuracy of resource estimates compared to conventional methods (Erik Næsset stresses the importance of taking into account down-stream cost savings thanks to better decision making i.e. cost-loss analysis)
- Lower inventory costs per hectare compared to conventional methods

- LiDAR-based solutions free up staff because of significantly reduced time spent collecting data in the field.
- dynamic rather than static stand boundaries increasing the ability to track change and update resource estimates.

Most of these benefits would appeal to Australian forest owners but cost will weigh heavily in any analysis. Table 2 compiles the cost estimates noted during this study tour and recent figures from literature. Some Australian LiDAR data prices (2007 quotes) were added for comparison. All costs are per hectare.

Table 2: Some indicative values of costs per ha (LiDAR data, data processing, complete solutions)

Country	Method	Project Size & LiDAR data density	Source	Cost LiDAR data	AP inter-pretation, data processing reporting	All inclusive .data collection .processing .reporting .management plan
Canada	Plot based	large area, 1 point/m^2	Ken Durst, pers comm.	A$0.5-1.0	-	-
Norway	Plot based	< 1 point per m^2	Brethvad pers. comm..	-	-	A$ 12-16
Norway	Plot based	20,000 ha, 1 point m^{-2}	Source: Eid et al, 2004	A$5.5	A$8.4	A$ 18.3
Sweden	Individual tree	10 point/ m^2	Jonmeister, pers comm.	-	-	A$ 12-23
Finland	Plot based	< 1 point per m^2	www.forest.fi	-	-	A$ 16-19
Finland	Plot based	30,000 ha	Leppanen, pers. comm	-	A$ 6.3	-
Finland	-	50,000ha, 5 point m^{-2}	(http://www.metla.fi/silvafennica/full/sf40/sf403531.pdf)	A$6.5	-	-
Finland	Plot based	5,000 ha, 5 point m^{-2}	“”	A$5.5	-	
South Australia	-	2.8 million ha, alt: 3000m, 0.3 points/m^2	Rombouts	A$ 0.35	-	-
		96,500 ha, 0.5-1 points/m^2	“”	A$ 2.8		
		8,200 ha, 0.5-1 points/m^2	“”	A$ 7.5		

The plot-based, low density inventories in Norway and Finland offer a comparable product, inclusive a management plan, at a comparable price (A$12-19 per ha). Surprisingly even the high density, individual tree-based inventory in Sweden is comparably priced (A$12-23).

LiDAR data prices in South Australia increase rapidly as the project area decreases mainly because of the fixed mobilisation cost of $40,000. Note however that if several (forest) organisations were to coordinate their data acquisition projects this mobilisation cost could be shared. The degree of fragmentation of the target area also determines cost.

The cost of LiDAR data/applications is predicted to decrease in coming years:

- LiDAR data is likely to become cheaper because for the same price of the instrument the capabilities of laser scanning systems will continue to improve. There are opportunities for cost savings through collective data acquisition. Juha Hyyppä suggests that data could be acquired by an independent agency and then on-sold to other parties – he refers to the example of Switzerland where the data acquired for the production of a National DEM were sold five times over. In Norway, collaboration with the National Mapping Authority to share costs for laser data primarily collected for topographic mapping results in a dramatic drop in laser costs for the forestry side (Erik Næsset). Finally LiDAR data may also become more affordable because of increased competition between service providers.
- Research is leading to optimisation of methodologies ensuring that minimal LiDAR and field data is collected for a given application.
- Research is leading to the development of new LiDAR applications so that more value can be added to the same investment in raw data. Increasingly forest holders around the world choose to demonstrate sustainability of their management practices and institute environmental monitoring programs in support of this. This is an area where new LiDAR applications are being developed.
- Commercial software will become available making it easier and less costly to deploy and maintain LiDAR solutions.
- Current research into using LiDAR as a sampling tool (flying strips rather than full cover) also has the potential to reduce cost.

Australian forestry organisations evaluating the use of LiDAR must consider all the possible benefits that can be derived from the data, including the long term benefits flowing on from better quality and spatially continuous data sets. With water being such a topical issue and topography being instrumental in understanding water in the landscape it is possible that investment in Digital Elevation Models could generate a significant long term return. In the case of Forest Plantations Queensland the production of a DEM alone justified investment in LiDAR data over the entire estate. In South Australia water management concerns provided the main driver for investment in a 2.8 million ha regional DEM.

The more applications can be developed for the same data set the more value can be added. A list of the potential applications of LiDAR data by ForestrySA, is compiled in Table 3 (ForestrySA is a radiata pine grower that also manages native forest for conservation purposes).

This list will look different for every company. Companies operating in vast expanses of less-intensively surveyed, less-accessible native forests may see more value for LiDAR in harvest planning and coupe design, not unlike Tembec in Canada.

In the case of ForestrySA many applications have yet to be tested for feasibility. The strategy will be to implement “easier” applications such as Site Quality assessment first and then to move on to the challenge of getting product information out of LiDAR-based pre-harvesting inventory.

Table 3: Possible uses of LiDAR data at ForestrySA

Application	Feasibility
DEM to assist plantation establishment (identifying no-spray buffers zones, deciding site preparation, planting row directions)	Building DEM is feasible even under densest plantation. Usefulness of DEM for establishment needs to be demonstrated, but trial has commenced.
DEM for hydrological modelling (water flows, depth ground water table)	Regional DEM is under construction. More research is needed to demonstrate correlation DEM and depth ground water table.
Site Quality assessment (young age volume mapping)	Successfully achieved on five sites
Pre-harvesting inventory	Feasibility to be demonstrated. Requires diameter distributions as a minimum.
Young age fertiliser decision support	Young age fertiliser application is decided based on volume growth at age 2.5-4.5. Feasibility has been demonstrated on one site.
Post-thinning fertiliser decision support	ENSIS research has demonstrated that the magnitude of fertiliser responses increases as Leaf Area Index (LAI) decreases. LAI can be estimated based on LiDAR data. Needs to be demonstrated.
Updating of stand maps following harvesting operations	Feasibility to be demonstrated.
Managing trees in proximity of power lines	Feasibility to be demonstrated
Bluegum plantation inventory (merchantable stand volume at age 10)	Feasibility demonstrated on one site
Native forest controlled burning management – fuel load assessment	Feasibility to be demonstrated

Access to expertise

Specialised forest information service companies such as Prevista, FORAN, Arbonaut, Lim Geomatics play an important role in making LiDAR technology accessible to the forest industry. In fact the business model that appears to be developing overseas is one whereby forestry companies, government bodies or associations of forest owners are contracting out part or all of the assessment projects to specialised service companies. Large companies such as Tembec Inc and BPH only contract out heavy duty number crunching. Other companies want comprehensive solutions. Different service companies offer information at different levels of detail and price. Competition between companies is likely to increase. Many of these service companies have ongoing links with academia. Many of their key staff have a background in LiDAR research.

Comparable service companies offering neatly packaged LiDAR solutions do not as yet exist in Australia. Research organisations such as Ensis can assist companies in implementing operational trials but do not yet provide an operationally-oriented service. Expertise is scattered over several universities and is not geared towards service provision.

The lack of easy access to forestry-oriented LiDAR services takes LiDAR out of reach of forest companies that lack the inclination to invest in development of internal capabilities or operational trials.

Research needs

The research seen during this study tour was broad-ranging. Operationally-focused research seeks to optimise existing methods and may lead to cost savings through more efficient use of inputs. Development-oriented research seeks to develop new methods and capabilities and may add to the range of uses for LiDAR data. This activity will undoubtedly lead to increased capabilities to generate product information. New uses of LiDAR data for environmental applications also belong to the possibilities.

Australia should be able to identify with most of the research directions chosen overseas. However given the importance of product information to Australian forest growers, one of the most pertinent research questions is to what extent LiDAR data can assist in generating product information, either directly or indirectly (by improving the efficiency of conventional inventory). It may be possible to get to product information through LiDAR-based diameter and height distributions, taper models and bucking algorithms. Or as trialled in Sweden by imputation of harvester data. But these are by no means the only interesting lines of inquiry.

There is also a need for research into how LiDAR can assist health monitoring and nutritional status (fertiliser decision support).

The author was impressed by the size of research teams working on LiDAR-related topics. Nordic countries have programmes for exchanges between universities and some of the research projects are coordinated or shared across national borders. Universities cooperate with research organisations and the industry.

In comparison Australian LiDAR research activity is more geographically and organisationally fragmented. The positive response to recent events such as the “LiDAR in Forests” workshop in Hobart organised by the CRC for Forestry in May 2007 and the LiDAR sessions at Research Working Group 2 biennial meeting in Woodend in November 2006 suggests there is a real need for increased contact and exchange of experience between those active and/or interested in the LiDAR field.

The lack of robust and (commercially) available software is an impediment to more widespread use of LiDAR in forestry. It is therefore good news that several groups have started software development projects. The question is whether this will result in a toolbox with broad applicability or in a system with narrow focus. Will it be commercially available? Does the Ensis LiDAR toolbox provide a good starting point for an Australian initiative?

Some final remarks

Mike Wulder stressed that information needs should drive LiDAR application development and not the other way around. Implementation should be methodical and considered and care must be taken not to overstate the possibilities because this risks discrediting the technology.

Both Matti Maltamo and Timo Tokola advised to select the simplest method capable of producing needed outcomes.

Erik Næsset's work exemplifies this advice. Næsset set out and succeeded in developing a robust and practical LiDAR application that could match the outcomes of existing operational forest inventory methods. And through thorough validation he made sure to back up the results.

Any deployment of new measurement techniques must consider consistency with existing approaches. Juha Hyyppä however cautions against unquestioningly accepting existing approaches as the accuracy benchmark. In some cases more accurate results can be achieved with LiDAR especially if existing approaches are subject to measurement, sampling, modelling or implementation error.

Itinerary

People met during the study tour

Zhenkui Ma
Weyerhaeuser HQ, near Seattle, USA

Weyerhaeuser is a large multi-national integrated forest company with several daughter companies in Australia and New Zealand. It is of obvious relevance to learn whether this company sees a place for LiDAR in its management practice. Dr Zhenkui Ma is the Remote Sensing consultant at Weyerhaeuser advising on operational implementation of remote sensing techniques throughout the company.

Stephen Reutebuch and Bob McGaughey
Silviculture and Forest Models Team, Resource Management & Productivity Program, Pacific Northwest Research Station, USDA Forest Service; University of Washington, Seattle USA

The US Forest Service is the largest forest land owner in the United States. It is also responsible for the US National Forest Inventory. The team headed by Stephen Reutebuch (which until recently also collaborated with Hans-Erik Andersen), forms the focal point of LiDAR research in the US Forest Service. The team published papers on accuracy of Digital Terrain Models under forest cover, individual tree segmentation techniques, fire behaviour modelling applications. Bob McGaughey is the main developer of the Fusion LiDAR data processing and visualisation system. He also developed the EnVision forest visualisation software. During my visit I was introduced to UoW students Sooyoung Kim (PhD) and Jacob Strunk (MSc) and visiting PhD candidate Johannes Breidenbach of the Forest Research Institute of Baden-Würtemberg.

Mike Wulder, François Gougeon, Don Leckie
Pacific Forestry Centre, Canadian Forest Service, Victoria, Canada

The Pacific Forestry Centre has made many significant contributions to the LiDAR literature and plays an important role in the Canadian Forest Service as a R&D centre and as the seat of the Canadian NFI. Mike Wulder is interested in the problems associated with integrating resource information over a range of spatial scales and has worked with many types of remote sensing data including LiDAR. François Gougeon has spent twenty years developing methods to detect and measure the attributes of individual trees on high resolution optical imagery; methods which are also applicable to fused LiDAR-optical imagery. Don Leckie is one of the pioneers of LiDAR research in Canada having contributed to the first trials in the early eighties. He has also explored the complementary qualities of multi-spectral and LiDAR data for individual tree measurement.

Nicholas Coops, Chris Bater, Nick Goodwin
Faculty of Forestry, University of British Columbia, Vancouver, Canada

Many in Australian forestry circles are familiar with the work done by Nicholas Coops at CSIRO. Currently he holds a Canadian Research Chair in Remote Sensing at UBC. He teaches Remote Sensing to Forest Conservation students and supervises 8 post-graduate students. Chris Bater is a Masters student working on assessing sustainability indicators. Nick Goodwin (also Australian) just finished a PhD on Eucalypt forest understorey assessment using LiDAR and has just commenced a post-doctoral position in Nicholas' team.

Benoît St-Onge
Université du Québec, Montréal, Canada

Benoît St-Onge is professor Remote Sensing at the Department of Geography. His idea was to develop a hybrid LiDAR-optical imagery method whereby LiDAR data is used to model bare earth under forest canopy while optical imagery is used to model the forest canopy surface. Professor St-Onge is active Canada-wide and supervises several PhD candidates working on LiDAR topics.

Paul Courville,
Enhanced Forest Inventory Project, Forest Research Partnership, Canadian Ecology Centre, Mattawa, Canada

The Enhanced Forest Inventory project is one of several projects of the Enhanced Forest Productivity Science program funded. Partners in the project are the Ontario Ministry of Natural Resources, Tembec, Canadian Forest Ecology Centre, Queens University, Canadian Forest Service. Its main objective was to investigate high-resolution digital imagery integrated with airborne LiDAR data leading to the production of enhanced forest inventories in the Great Lakes-St Lawrence forest region. The project is connected and coordinated with a similar project initiated by Tembec in boreal forest of NE Ontario. Paul Courville is Logistics Officer in the project and provides GIS and system expertise.

Paul Treitz, Valerie Thomas
Department of Geography, Faculty of Arts and Science, Queens University, Kingston, Canada

Paul Treitz is Associate Professor, Acting Head of the Geography Department of Queens University and heads the Laboratory for Remote Sensing of Earth and Environmental Systems. He has conducted/supervised LiDAR-related research since the late nineties and was one of the partners in the Enhanced Inventory project mentioned above. Students supervised include Valerie Thomas, Chris Hopkinson, Kevin Lim, Laura Chasmer.

Erik Næsset, Liviu Ene
Dep. of Ecology and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

Professor Erik Næsset's laser scanning work started in the mid 1990's. His focus was on the development of a practical and robust LiDAR based forest inventory method suitable for Norwegian forest conditions. Characteristic of this work was the comprehensive and independent validation of results. His method is gradually replacing the conventional photogrammetry based inventory methods in Norway. It has also been applied successfully in several other countries (including by ForestrySA in Australia). Liviu Ene is a brand-new PhD student and will be working on field sampling strategies for the purpose of LiDAR data calibration.

Thomas Brethvad, Svein Håvard, Floris Groesz, Erik Iversen
Prevista, Kongsberg, Norway

Prevista was founded in 2001 through the merger of several companies thus becoming the largest forestry and land-use planning service company in Norway. They service about 40% of the productive forest area in Norway. Since 2004 the company offers LiDAR based forest inventory as an alternative to conventional inventory techniques. The company also has an international consulting arm. Thomas Brethvad is the Director of the Forestry Department, Erik Iversen is “Forest builder”, ie the photogrammetry expert responsible for stand delineation and stratification, Svein Håvard is the GIS analyst responsible for packaging project outputs in spatial data sets, Floris Groesz is a remote sensing-GIS specialist.

Johan Holmgren, Mats Nilsson
Laboratory of Remote Sensing, Department of Forest Resource management and Geomatics, Faculty of Forest science, Swedish University of Agricultural Sciences, Sweden

The Laboratory of Remote Sensing comprises of a team of 22 staff headed by Professor Håkan Olsson. Johan Holmgren developed new methodologies to extract stand information from LiDAR data, including the differentiation of species based on crown shape. He also worked on the importance of data collection parameters such as scanning angle and wrote up the first operational LiDAR based forest inventory trial in Sweden. Mats Nilsson has extensive experience in remote sensing and was one of the first to study LiDAR forestry applications commencing in Sweden in 1991.

Juha Hyyppä
Finnish Geodetic Institute, Masala, Finland

The Finnish Geodetic Institute is a research institute for the mapping sciences. Professor Juha Hyyppä heads the Department of Remote Sensing and Photogrammetry. He was one of the first to develop algorithms for the extraction of individual tree information from LiDAR point clouds. His team also carried out extensive studies to assess the accuracy of LiDAR-derived Digital Terrain Models and demonstrated that high density LiDAR data collected before and after a harvesting operation could be used to reliably determine which trees had been removed. Juha Hyyppä also coordinated the EU funded HIGHSCAN project aimed at forest stand attribute assessment by integrated use of high-resolution satellite imagery and laser-scanner and involving Finnish, Austrian, German and Swiss universities and companies.

Matti Maltamo, Timo Tokola, Pettri Packalén
Faculty of Forestry, University of Joensuu, Joensuu, Finland

The Faculty of Forestry at the University of Joensuu is one of the two main Universities offering forestry degrees in Finland. Matti Maltamo is Professor Forest Mensuration. His expertise in diameter distribution modelling has more recently been applied towards the extraction of diameter distributions from LiDAR data. He currently supervises 6 PhD students whose projects all involve LiDAR data in some capacity or other. Timo Tokola is Professor Forest Information Systems. He is currently involved in a project to develop the next generation Finnish forest planning system (SIMO). In view of his extensive expertise in remote sensing he is also supervising a Master and PhD student working on individual tree recognition using dense LiDAR data sets or multi angle high resolution digital imagery. Pettri Packalén is Senior Assistant Forest Mensuration whose area of expertise is the combination of aerial photography and LiDAR data.

Kari Korhonen
METLA (Forest Research Institute Finland), Joensuu, Finland

METLA is responsible for implementing the National Forest Inventory of Finland. Kari Korhonen is coordinator of the NFI's field data programme. Earlier in his career he was responsible for management inventory and hence had a good overview of the various flavours of inventory in Finland.

Vesa Leppanen
Arbonaut Oy, Joensuu, Finland

Arbonaut Oy offers enterprises and associations products and services to manage forest and other natural resources. The company offers LiDAR-aerial photography inventory services to the industry and is currently involved in a pre-operational project with large company UPM. Vesa Leppanen is the Manager, Remote Sensing.

People who contributed by e-mail

Ken Durst, Tembec, Canada
Ken Durst is Forest Information Management Coordinator at Tembec, Inc and A/Extension Manager at the Forest Research Partnership. Ken was unavailable when I visited Mattawa. He clarified Tembec's position with regard to LiDAR by e-mail.

Tobias Jonmeister, FORAN, Sweden
Tobias Jonmeister is Production Manager of FORAN, a Forestry and Nature consulting company based in Sweden. FORAN was mentioned during visits to other people as a service provider that recently started offering LiDAR solutions. The company indeed set up a new subsidiary named FORAN Remote Sensing that offers a "Single Tree" laser service, meaning that the smallest resolution at which information products are provided to customer is the individual tree.

Juho Heikillä, Forest Development Centre (TAPIO), Finland
TAPIO provides consulting and development services, training and IT solutions to customers in government (Ministry of Agriculture and Forestry, Forestry Centres, Forest and Park Service) and private sector (Forest Management Associations, forest industry). TAPIO plays an important role in decisions with regard to forest inventory methodology. Juho Heikillä is remote sensing expert at TAPIO. He was unavailable during the study tour but provided extensive information by e-mail.

Håkan Olsson, Swedish University of Agricultural Sciences
Professor Håkan Olsson heads the Laboratory of Remote Sensing at the Swedish University of Agricultural Sciences (see above).

To all of you many thanks.

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