Abstracts

Airborne laser scanning based stand level management inventory system of Finland.

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In Finland, a new ALS based stand level management inventory was developed during last few years. The system is based on area based approach of ALS data. Additionally, the spectral and texture features of the aerial images are utilized in order to improve the separation of the tree species. The species-specific stand attributes are simultaneously estimated with a nearest neighbour imputation. The new airborne laser scanning based stand level management inventory system has been successful. During just a few years almost all actors of practical forestry have modified their inventory and planning systems to be compatible with the new inventory procedure which will cover almost 3 000 000 hectares in 2011. This paper describes the background, development and practical application of this inventory system.

Notes:

A national review of airborne lidar application in Australian forest agencies

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This paper provides a narrative of airborne lidar application across Australian forest agencies. It includes a brief history of early lidar research and operational trials, as well as current programs and future directions on a state by state basis. This review demonstrates a diverse range of lidar applications and increasing adoption of lidar technology within state agencies across Australia.

Airborne LiDAR based forest inventory in Bangladesh for REDD plus MRV: scope and potentiality

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Nowadays, the accurate measurements of carbon stock for carbon trading in REDD plus (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) countries are going highly demanding. IPCC (Intergovernmental Panel on Climate Change) Tier 3 level accuracy for estimation of emissions from deforestation and forest degradation requires detailed national inventory of key carbon stocks, repeated measurements and modeling. Present study has been carried out to know scope and potentiality of the airborne LiDAR based forest inventory in Bangladesh for REDD plus MRV (monitoring, reporting and verification). Here we supposed a hybrid method where the integration of airborne LiDAR data with satellite imagery and ground truth data based forest inventory in Bangladesh. As the forest of Bangladesh is highly dynamic and inaccessible due to hilly and mountainous area, this method will give an accountable and transparent report of carbon stock. We also highlighted the limitation of this approach in a developing country like Bangladesh due to poor economic and technical condition. Till now there is no record of application of airborne LiDAR system for forest inventory in Bangladesh. Finally, we recommended that the Forest Department of Bangladesh with financial and technical help from international organization can do a pilot project in Sundarban Mangrove Forest.

Stand level inventory of eucalypt plantations using small footprint LiDAR in Tasmania, Australia

Robert Musk

Models derived using Brieman's Random Forests algorithm have been identified in past studies as having greater predictive accuracies than those derived using nearest neighbour imputation approaches. This is attributed to the algorithms ability to model complex interactions among predictor variables and its resistance to overfitting. These two properties are of particular value in modelling LiDAR-derived variables where strong colinearity is a common feature. In this study, the random forest algorithm is applied to a large inventory dataset to generate mapped estimates of forest stand structure. The ability of the algorithm to identify an optimal set of candidate variables is assessed by means of an iterative model fitting procedure. The study area comprises a eucalypt hardwood plantation estate in northern Tasmania, Australia. Model pseudo R2 values were 74.6% for basal area, 96.0% for mean dominant height, 64.2% for stocking and 83.9% for merchantable stand volume respectively.

Building a case for lidar-derived structure stratification for Australian softwood plantations

Russell Turner*, Amrit Kathuria, Christine Stone

Conventional resource inventories in Australian softwood plantations usually utilise Geographic Information System (GIS) thematic layers to stratify the resource prior to field sampling. Airborne lidar can offer a viable alternative for stratification but there are no standardised methods for plantation managers. This paper explores issues with current thematic stratification approaches and argues that relatively basic metrics extracted from a lidar-derived canopy height model (CHM) are suitable for constructing better stratification options. The case is supported with findings from an airborne lidar inventory undertaken in a pine plantation in New South Wales (NSW), Australia. Lidar stand level metrics including mean height, mean above mean height, mean dominant height, predicted stocking, canopy cover percentage, occupied volume and height variance were tested as surrogates for plantation structure. The study demonstrated that lidar metrics can predict stand attributes such as age class (R^2= 0.91, RMSE 1.9%), thinning treatment (89% accuracy), mean height, (R^2= 0.95, RMSE 4%), stocking (R^2= 0.82, RMSE 26%), basal area (R^2= 0.67, RMSE 19%) and total stand volume (R^2= 0.8, RMSE 19%) across a range of stand structures. Since the metrics tested were highly correlated with survey data it is argued that they could provide a valid basis for a developing a new structure stratification approach to improve sampling design in future plantation resource inventories.

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Ground based and airborne lidar - a natural combination

David Jupp

When, at the end of the 20th century, a group from CSIRO (Australia) was evaluating support (aka seeking funding) for their ideas about combined airborne and ground based Lidar, the ground based system they proposed was seen as an adjunct for on-ground checking. But their common experience with forestry and environmental companies was lack of interest in airborne and amazing enthusiasm for ground based. Perhaps the idea of a measurement tool that was not remotely operated by someone else but was in the forest and operated by them was what was attractive. Whatever the reason, that group has been focused on ground based Lidar ever since. I am sure this is not an uncommon experience, but perhaps ground based systems are not yet fulfilling that observed interest to become an ubiquitous component of forest measurement.

One possible reason for this is that ground based (GB) and airborne (AB) systems need each other and that will be the somewhat "rhetorical" topic of this talk. A major combined use that has been suggested is that GB can be used to "calibrate" or "validate" AB. "Calibrate" means setting parameters for data interpretation of AB such that it generates biomass or something else of interest over a wide area. "Validate" means to ensure that such wide area information is staying sufficiently close to the truth to be useful. If this were not enough, people may suggest that GB samples an area and AB can extend the sampling to a wide area containing the samples. But this is not too different from calibration. Again, in tall and dense forests the two systems may provide "handshaking" between information about the upper and lower parts of the forest.

It is tempting to look at GB and AB as the same activity from different "platforms", but this is not quite correct. GB systems are really not necessarily fixed to the "ground" but rather work from a fixed reference coordinate system allowing multiple angles and multiple volumes sampling from a number of locations – even from above the canopy. I believe AB is characterised by the dynamical nature of its collection system and is much more similar to space-borne (SB) systems than to GB systems. Accepting this definition, we can consider measurement strategies for GB systems that will be called "extensive" strategies and "tomographic" strategies. The first aims to collect as much information as possible from a single point of reference at a site and sample as many different (but possibly not overlapping) sites within a wide area as possible. The second aims to use multiple points of reference to sound the same volume to maximise information about the volume – which is usually necessarily a single site. Each of these must deal with the complex combinations of gaps, hits and occlusion within a forest and they tend to do it in different ways.

Within this framework, the talk will use the experiences of scientists mostly at CSIRO (Australia), Boston University, City University of New York and University of British Columbia to discuss the potential for successful integration of AB and GB systems. It involves issues of data compatibility (such as the use of intensity information, waveforms and calibration), sampling versus tomography and consistency of processing and interpretation models. It will be proposed that ultimately, the realisation of the integration involves deriving a "transfer function" between measurements in the two systems. This function must, by the nature of the systems, be statistical and can be empirical or model based. Of all the possibilities, model based transfer is the one that probably interests scientists most and the talk will illustrate how the groups above have progressed towards this end. Finally, it should be pointed out that there may be more answers to the questions posed here in the presentations at the conference than there are in the talk. Hopefully, that will be the case. The main objective is to address the issues and look to the work of the many scientists now working in AB and GB Lidar to make it happen.

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Harvesting productivity analysis using LiDAR

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Mechanised harvesting operations are common in Australia because of their increased productivity and efficiency, improved worker safety and reduced cost of operations. Most research has found that the productivity and efficiency of a mechanised harvesting system is affected by a number of factors including forest stand characteristics (tree size or piece size, stand density, undergrowth), terrain variables (slope, rocks, woody debris), operators' skill and machinery limitations. The purpose of the study was to use remote sensing technology to quantify these forest stand and terrain factors (particularly slope) and hence derive relationships to predict harvester productivity from remote sensing data. A case study was conducted in mature radiata pine (*Pinus radiata*) plantation at Mount Burr Reserve Forest, South Australia (37.61° S, 140.44° E). LiDAR (Light Detection And Ranging) flown in 2007 was used to identify and quantify stand and terrain factors (particularly tree size). A time and motion study conducted during final harvest was used to estimate the impact of each factor (tree size and slope) on harvester productivity. Tree size estimates derived from the LiDAR data were grown to the point of harvest using empirical growth models. The point of harvest tree size estimates were ground-truthed against harvester measurements of the same trees. Empirical models were then developed to enable the LiDAR-derived estimates of tree size to be used to estimate productivity of harvesting equipment. The robustness of these relationships will be tested by applying the model to areas not used in the development process.

Scaling plot to stand-level lidar to province in a hierarchical approach to map forest biomass in Nova Scotia

Chris Hopkinson, David Colville*, Danik Bourdeau, Suzanne Monette, Robert Maher

This paper presents a study that used lidar transect, plot and wide area polygon sample data collected across Nova Scotia, Canada from 2005 to 2010 to calibrate and extrapolate above ground forest biomass from permanent sample plots (PSPs) to forest stand polygons to the entire Province. The whole tree dry biomass estimate for the total forest resource inventory (FRI) database in Nova Scotia is ~ 373x 106tonnes ±39%. Where lidar coverage exists, biomass is modelled at the 25 m grid cell resolution, which is a great improvement over the previous eco region level estimates, allowing for more effective operational stand management. Given the large spatio-temporal domain of the data sources, one of the major challenges faced in this study was temporal latency between coincident field, lidar and GIS data inputs, which was a significant contributor to the overall level of uncertainty in the result.

Estimating stand volume from nonparametric distribution of airborne LiDAR data

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This study was performed to estimate stand-level volume using the characteristics of vertical and horizontal distribution of airborne Light Detection And Ranging (LiDAR) data. It is found that the height distributional parameters, such as percentile, of LiDAR data reflected on-and in-canopy in a stand have the relationship with stand volume in previous research. However, we assumed that the nonparametric height distribution form of canopy LiDAR returns would be obviously related with the stand volume directly. Nonparametric height distribution was presented to be a continuous line according to the frequency of LiDAR returns by the height. Thereafter, the sum of each height of all canopy returns, which means the area below the continuous line, was compared to stand volume using National Forest Inventory (NFI) data. In addition, for verifying the volume of test stands, the similarity which is the overlapping ratio between the height distribution curves of sample and test stand was calculated. The relationship between the height sum and stand volume was relatively highto be R^2=0.83. Based on such relationship, the maximum similarity of each test stand was computed as compared sample stands. As a result, mean similarity and root mean square error (RMSE) of estimated stand volumes were 82% and 34.96m^3/ha respectively. However, supplementary indices, for non-overlapping part in similar distribution of canopy returns of sample and test stand, are needed to reduce such errors.

A method for linking TLS- and ALS-derived trees

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Within the past decade progress towards automatic recognition of individual trees and their parameters was made in both TLS and ALS-data based algorithms. In this paper we present an approach to combine single trees derived from ALS and TLS-data in order to gain a higher level of information. Therefore, two data sets are used: 1. a set of 3D-stemfiles generated by the algorithm described in Bienert *et al.*2007 and 2. a set of detected single trees for the corresponding area of the data set 1 based on the algorithm described in Gupta *et al.*2010. The 3D-stemfiles include position, information regarding sweep and diameter in 10cm height intervals. The ALS-tree description covers the position, maximum crown diameter and length as well as tree top height. This information is used for a hierarchic approach of linking ALS and TLS-derived trees based on three different initial matching algorithms. The estimated position error is taken into account to generate an initial list of matching candidates. The 2D-distance based initial linking method linked 41% of the TLS-trees. It was found that 3D-estimation of the tree top based on sweep information of the TLS-trees led only to minimal more imputations than the 2D-approach. A possible reason is seen in the linear models chosen, which do not reflect the tree shape invariably. Future work focuses on the integration of species information and the quantification of false linkage, which could not be evaluated within this study.

Reducing extrapolation bias of area-based k-nearest neighbour predictions by using individual tree crown approaches in areas with high density airborne laser scanning data

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K-nearest neighbour (kNN) approaches are popular statistical methods for predicting forest attributes in airborne laser scanning (ALS) based inventories. Their main upsides are the simplicity to predict multivariate response variables and their freeness of distributional assumptions on the conditional response. One of their largest draw-backs is that predictions outside the range of the reference data inherently result in an under-or overestimation. This property of kNN approaches is known as extrapolation bias and aggravates with an increasing number of neighbours (k) used for the prediction. This study presents one possibility to reduce extrapolation biases of predictions based on the area-based approach (ABA) by using individual tree crown (ITC) approaches within those specific areas of a low density ALS acquisition where the point density might be sufficiently high for using ITC methods. In the proposed strategy, additional (or artificial) reference plots augmented field measured plots. Artificial plots were created by applying ITC segmentation to a canopy height model derived from high density ALS data. The response variable biomass per hectare was predicted for every segment following a semi-ITC approach. The segment predictions were aggregated at the artificial plot level. The artificial plots were then treated in the same way as the original reference data to make predictions in areas with low density ALS data based on the ABA. It was hereby assumed that the predicted plot level response on the artificial plots is equivalent with the observed plot level response on the original reference data. The data consisted of 110 reference plots with a smaller data range than the 201 independent validation plots. Considerable extrapolation bias was visible if only the reference plots were used for the prediction. Almost no extrapolation bias was found if the prediction was based on reference plots augmented by artificial plots. The root mean squared error (RMSE) of the biomass predictions based on the reference plots was 39.1%. The RMSE reduced to 29.8% if the reference plots were augmented by artificial plots.

Stem detection and measuring DBH using terrestrial laser scanning

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Plot-level forest inventory information is critical for forest management; however, acquisition of forest structural attributes is a time consuming, costly, and often inconsistent, task. Recent developments have utilized terrestrial laser scanning (TLS) for rapid acquisition of forest structural detail as point cloud data, suitable for conversion to forest attributes using appropriate algorithms. Processing of these data remains a non-trivial task. In this paper, an efficient and robust method for stem detection from terrestrial laser scanning is presented based on the Medial Axis Transformation. The algorithm effectively eliminates outliers such as branches and uses a small number of parameters. Results show robustness of model parameters and minor errors of commission, while errors of omission are a function of range distance from the scanner. For horizontal distances up to 10 meter from the scanner 86% of trees manually detected from the scans could also be detected automatically. This includes some very small trees (<10 cm) that would not have been included in field inventories. Implications of the current algorithm and related data requirements on acquisition protocols are discussed.

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Tree biomass estimation using ALS features

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Today the estimation of biomass and detection of changes in biomass in large areas is based on coarse remote sensing data and field measurements, which are time consuming, expensive and, above all, in local level inaccurate. The recent development of techniques has offered opportunities to develop new methods, e.g. laser scanning. Airborne laser scanning (ALS) derived features could be used to estimate the total biomass of standing trees. The objective of this study was to make preliminary investigations between accurately measured biomasses in the field and ALS derived features. Study material consisted of 38 sample trees: 19 Scots pines (*Pinus sylvestris*) and Norway spruces (*Picea abies*), which biomasses were accurately measured. ALS derived segments representing the field trees were matched and features for trees were extracted from ALS points within segments. Correlations between biomasses and ALS features were calculated and simple regression models were formulated. The relative residual errors were 21% for Scots pine and 40% for Norway spruce. More empirical tests are needed for ALS based tree biomass estimations.

Stand level species classification and biomass estimation using LiDAR height, intensity, and ratio parameters

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In this study we use airborne LiDAR to classify tree species and estimate volume at the stand scale using multiple linear discriminant analysis and multiple linear regression analysis. This involved the extraction of 38 independent variables from LiDAR data including height, intensity, and ratio metrics. In stand species classification, the 90 percentile of height (*HC,90*), standard deviation of the intensity (*IC,std*) and vegetation intensity ratio (*VIR*) were the most suitable variables for explaining each stand species. Hit ratio represented by accuracy in discriminant analysis was 81.7% in stand species classification. Afterward, the regression models were estimated using each variable, with the best model then selected using the corrected Akaike's Information Criterion (AICc). *HC,90* , mode of intensity (*IC,mode*) and standard error of mean of intensity (*IC,se*) were applied to optimally explain the stand volume of Japanese Larch (*Larix leptolepis*), with an R^2=0.83. With the mean of height (*HC,mean*), mode of height (*HC,mode*), standard deviation of intensity (*IC,std*) and range of intensity (*IC,range*) could be used to predict the stand volume of Japanese red pine (*Pinus densiflora*), with an R^2=0.79. Finally, the 80th height percentile (*HC,80*), *IC,mode* and the kurtosis of intensity distribution (*IC,kurt*) were applied to predict the stand volume of Oaks (*Quercus* spp.) with an R^2=0.68.

Effect of scan coverage on stem diameter measurement using terrestrial LiDAR

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This paper presents a new approach to measure stem diameters based on the data acquired by multiple scanning by terrestrial lidar. Recent terrestrial lidar (Riegl VZ400) has wider coverage and is able to efficiently

provide the highest point density data. Stem diameter derived from terrestrial lidar was compared with field measured diameter at breast height (d.b.h) of 42 sample trees. Stem returns of d.b.h were extracted and used to identify the approximated stem centre using principal component analysis. Various scan coverage of stem returns was used in the algorithm developed in this study to assess which is the most appropriate to measure stem diameter. The results show that more than 40% scan coverage of stem returns can produce stem diameter with an error of 5 cm or less using the algorithm. The applied technique can also assess the quality of wood by estimating straightness of stems from the alignment of stem centres at several heights. Furthermore, stem volume which is the most important variable to estimate the amount of carbon can also be measured directly using this technique.

Stem curve measurement using terrestrial laser scanning

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Terrestrial laser scanning (TLS) has been shown to be a promising technology for the accurate forest inventory on the sample plots. The advantages of applying TLS can be improving the accuracy and efficiency of the field measurements. In addition, TLS data have the possibility to provide more tree parameters than what are commonly accepted and employed at the moment. This paper discusses the automatic measurement of the stem curve using TLS. A pine and a spruce were used in the experiment. The stem curve estimated from point cloud was compared to the field measurements. The experiment shows that the estimation of the stem curve from single-scan and merged point clouds are comparable to each other. This result indicates that TLS data has the potential to automatically estimate the stem curve.

Estimating single-tree branch biomass of Norway spruce by airborne laser scanning

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Dry weight of the branches of 20 trees of Norway spruce was obtained through destructive sampling. Airborne laser scanning data from the same trees were used to calculate crown volume for each tree. The crown volume was derived by using the crown laser echoes with a radial basis function to construct a crown surface. A regression model was fitted to the data, with the crown volume as explanatory variable and the dry weight of the branches as response. The model revealed a strong relationship between the two, with $R^2 = 0.80$. A leave-one-out cross-validation gave a root mean square error of 34%.

Airborne laser scanning-based stem volume imputation in a managed, boreal forest area: a comparison of estimation units

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In typical airborne laser scanning (ALS)-based inventories, the forest is aggregated from initial estimation units, for which the attributes are produced using variable imputation techniques. The initial units vary in size and shape, being usually either regular grid cells or segments derived from the ALS data. This study compared small grid cells and segments of trees or tree groups as initial estimation units in an ALS-based estimation of species-specific, plot-level volume. The experiments were carried out in a managed, boreal forest area in Eastern Finland, where pine was the dominant species, and spruce and deciduous trees formed the other species groups. The field data consisted of 79 sample plots (400–900 m^2 in area) and the ALS data had a density of about 12 pulses/m^2. The estimation was overall very accurate, resulting in best-case root mean squared errors

of 13% for the total volume, 23% for pine, 49% for spruce and 90% for the deciduous trees at the plot-level. The total volume was estimated most accurately using a method in which 0 to *n* trees were imputed per segment. However, the differences between the estimation units were minor. Despite the significant biases in the estimates, the species-specific estimation was most accurate using a single-tree approach, i.e. by considering only the largest trees per segments in the imputation. The species-specific biases were of the same magnitude than the volume not detected by the tree detection algorithm, indicating that the proportion of the detected trees was estimated very accurately.

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Lidar in Australia - Progressing from digital elevation models to environmental monitoring

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There has been significant investment into acquisitions of airborne lidar data across Australia. The main drivers have been tsunami and sea-level rise risk assessment, flood modelling, communications, transport and urban infrastructure planning, mining, forestry, environmental assessments and emergency management. In most cases, the focus has been on the generation of accurate digital elevation models (DEM's). However, these lidar datasets include a range of vegetation types, streams, gullies and other landscape features of interest and provide a baseline for monitoring changes in vegetation structure and terrain over time. The benefits of existing airborne lidar datasets for monitoring applications will be discussed using a number of case studies. This includes monitoring change in vegetation structure over a 10-year period in Queensland, calibration/validation of products derived from spaceborne sensors, assessing streambank erosion along the Lockyer Creek in Queensland following the major floods in 2011 and monitoring gully erosion for selected sites in Great Barrier Reef catchments.

Future large area captures will also be discussed including an overview of the monitoring initiative by Ergon Energy aiming to cover a corridor of 150,000km in Queensland on an annual basis. The key challenges in establishing and continuing monitoring programs using airborne lidar technology will be highlighted. These include: (i) field calibration data requirements (including terrestrial lidar); (ii) survey control and uncertainty assessment; (iii) the methods used to generate derived products such as DEM's or forest and woodland metrics; (iv) sensor characteristics; and (v) data capture specifications. The authors believe that lidar-based environmental monitoring will grow significantly in Australia and best use of these data poses a number of important research questions. With open access to current and future lidar datasets by the research community, as well as the appropriate funding support, this technology will increasingly support environmental planning and policy decision making in Australia.

Notes:

Applying terrestrial LiDAR to derive gap fraction distribution time series during bud break

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The scientific community is witnessing a significant increase in the availability of different global satellite derived biophysical data sets. However, the use of such data is currently not supported by accurate in-situ biophysical measurement (e.g. canopy structure) in both a research and operational context for the monitoring of forest and land dynamics. Consequently, there is an urgent need for methods to measure in-situ canopy structure accurately and better integrate with improved and innovative remote sensing approaches. This paper explores the use of a ground-based, upward looking LiDAR instrument, combined with a fully automated analysis method to retrieve the gap fraction distribution. Traditional inventory methods for the assessment of forest structure are less objective or based on a 2D approach. We compare the seasonal dynamics of gap fraction distribution from hemispherical photographs and terrestrial LiDAR measurement during bud break.

Preliminary analysis shows that gap fraction distributions derived from terrestrial LiDAR were consistently lower than the values obtained from hemispherical photography. This might indicate that the LiDAR scans at the centre position of the plot are not representing the plot scale variation. However, the LiDAR based methodology is fully automated, requires no operator interference and is more objective, whereas the analysis of hemispherical photographs requires a large number of operator decisions (e.g. thresholding). Further improvements of this LiDAR-based method can still be achieved by (i) a better understanding of scanner settings and data resolution on the derived gap fraction and (ii) integration of target intensity in the analysis. This paper highlighted the high potential and need for a robust method to derive gap fraction distributions to monitor seasonal dynamics in forests.

Foliage profiles from ground based waveform and discrete point LiDAR

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Terrestrial lidar systems provide a means to characterise the structure of a forest canopy. Their use to measure foliage area volume density depends on the ability to account for sampling effects and intensity calibration of the instrument. This paper presents a theoretical framework for the unbiased calculation of foliage amount using a waveform recording lidar instrument to simulate point cloud data. The method is initially based on the hemispherical scan configuration of the instrument, but is generalised to be applied to point cloud data in a generic coordinate system. The theory is tested with the simulated point cloud data as well as data from a commercial instrument. Foliage profiles from the terrestrial lidar instruments and airborne lidar are compared.

Generating an automated approach to optimize effective leaf area index by Canadian boreal forest species using airborne LiDAR

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Obtaining forest structure data to compute leaf area index (LAI) can be a challenge in remote areas like the Canadian boreal forest. Light ranging and detection (LiDAR) data provides a 3-dimensional view of the forest

that can be calibrated with minimal field data requirements relative to other remote sensing data. Our objective is to develop an automated method for combining a limited amount of field data with LiDAR to generate estimates of LAI. To accomplish this we used geographic information system (GIS) tools to expand upon a physically-based gap fraction model by incorporating a process for optimizing extinction coefficient by forest species. In this paper we demonstrate a simple, efficient method for optimizing remote sensing-based estimates of canopy attributes from limited field data. We were able to reduce the RMSE in modelled effective leaf area index by an average of 0.48 across all species. Combining such simple model optimisation approaches with other automated LiDAR-based canopy attribute extraction procedures shows promise as we move towards ever greater levels of LiDAR forestry operationalisation.

Change detection of mountain vegetation using multi-temporal ALS point clouds

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Multi-temporal laser scanner data to be used in change detection studies will most likely be acquired with different sensors, flying altitudes, and system parameters. Therefore, calibration is probably needed in order to make laser returns from vegetation comparable between two laser data acquisitions. In this study, two ALS point clouds were acquired with different sensors and flying altitudes. The first data set had 11.5pointsm-2and was obtained in 2008 with a Top Eye MKII scanner and the second with a density of 1.1pointsm-2was obtained in 2010 with an Optech ALTM Gemini scanner. The test site was located in Abisko in northern Sweden with forest dominated by mountain birch. Six meter radius sample plots were placed in the forest-tundra ecotone and assigned one of the following treatments: (1) reference with no removal of trees, (2) removal of 50% of the total number of stems above 1.5m, and (3) removal of 100% of the total number of stems above 1.5m.Histogram matching was used to calibrate the two data sets and sample plots were then classified into the three treatments. The overall classification accuracy was 82% using only the proportion of vegetation returns from the canopy as explanatory variable. Features created from gridded laser data had overall higher classification accuracy than laser features created directly from the point cloud. Histogram matching made the two data sets comparable by reducing the difference between them. These early results show how changes can be detected even with different sensors, flying altitudes, and system parameters.

Stability of LiDAR-derived raster canopy attributes with changing pulse repetition frequency

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Laser pulse characteristics (pulse emission rate and inherent pulse properties) influence the representation of forest canopy structure using LiDAR data. As the use of LiDAR-derived models for large scale forest canopy characterization increases, there is a need to optimize flight configuration settings to achieve this efficiently, and to ensure that changes observed in multi-temporal growth studies are due to forest change and not flight configuration influences. Using an Optech Inc. ALTM 3100 airborne LiDAR sensor pulse repetition frequency (PRF) was systematically varied over seven flights, in a three hour period, over Acadian mixed-wood forest plots in Nova Scotia, Canada in July 2005. Canopy height and fractional cover models were created and analysed to determine if differences in sensor configuration settings influence typical LiDAR-derived raster representations of canopy structure. Preliminary findings for both canopy height and fractional cover models are evaluated and discussed.

Characterizing peat swamp forest environments with airborne LiDAR data in Central Kalimantan (Indonesia)

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We investigated how measures derived from both small footprints airborne Light Detection and Ranging (LiDAR) data and Ortho-Photo images can be used to characterize Peat Swamp Forest (PSF) environments in Central Kalimantan (Indonesia). In August 2007 we mapped by helicopter several transects using Riegl LiDAR (LMS-Q560) Technology. In this study, our main objectives were:

a) to evaluate the peat surface/profile and their associated domes;
b) to estimate the dependence of tree canopy height with both peat dome thickness and peat dome slope variations;
c) to estimate Above Ground Biomass (AGB) variations based on tree canopy height and physiognomy variations; and
d) to demonstrate the applicability of LiDAR technology to detect logging activities in tropical peat swamp forest environments.

Additionally, we would like to demonstrate the first results of our second LiDAR survey conducted in August 2011. We found that in an undisturbed tropical PSF area the average tree-height increased from 15.32m (2007) to 17.18m (2011) by difference of 1.86m which is 12%. This clearly shows the forest recovery capacity in secondary tropical PSF under protected conditions (e.g. conservation status). Hence, we would like to demonstrate preliminary results of change detection method over this endangered ecosystem as well as the retrieval of forest attributes (e.g. AGB, LAI, Canopy Coverage, etc) in the frame of REDD+ knowledge.

Notes:

Comparison of the spatial pattern of trees obtained by ALS based forest inventory techniques

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The spatial pattern of trees in a forest can be defined as the locations of the trees in relation to each other. The spatial arrangement of a point (e.g. tree) pattern may be random (Poisson), clustered or regular. In this study the spatial pattern of trees was determined at the plot level by using L function, which is a square root transformation of Ripley's K function. The spatial pattern of tree was summarized in to three classes: regular, random and clustered. The study was carried out with 79 sample plots located in a managed forest area in eastern Finland. Tree maps were produced with the individual tree detection (ITD) and semi-individual tree detection (Semi-ITD) and spatial patterns of trees were calculated from the tree coordinates. The spatial pattern of trees was also predicted directly by using patch metrics calculated from the canopy height model as explanatory variables (AREA). The low resolution airborne laser scanning (ALS) data was used in the AREA and the high resolution data in the ITD and Semi-ITD. The Kappa value for the ITD was almost zero, which indicates virtually random classification. The AREA and Semi-ITD methods were clearly more accurate than the ITD. Kappa values for the Semi-ITD and AREA were 0.34 and 0.24, respectively, which nevertheless cannot be considered to be very good. However, determining the spatial pattern of trees by ALS is somewhat unexplored field of study. It should be studied how well the spatial pattern of trees can be determined in different type of forests.

Fusion of airborne LiDAR and WorldView-2 MS data for classification of depth to permafrost within Canada's sub-Arctic

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The discontinuous permafrost zone of north-western Canada is characterised by a heterogeneous landscape of tree-covered permafrost plateaus that rise 0.5 m to 2.0 m above the surrounding fens and bogs. The depth to permafrost or “frost table” is influenced to some extent by vegetation canopy cover, which drives complex feedbacks related to permafrost thaw. Spectral remote sensing offers the possibility of large area mapping of canopy and ground surface characteristics that may be used as a proxy for permafrost thaw within remote northern areas. However, this depends on whether or not spectral band scan be used to identify slight variations in vegetation characteristics. The following study compares vegetation and topographic characteristics obtained using airborne Light Detection And Ranging (LiDAR) with high spatial resolution WorldView-2 spectral bands and *in situ* transect measurements of the depth to frost table. The results of this study indicate that the depth to the frost table is related to above ground vegetation cover and tree height, yet relationships are complicated by canopy and under story characteristics, topographic derivatives, and the position of the measured frost-table transect within the fragmented plateau. Comparisons between vegetation structural characteristics and WorldView-2 spectral bands are also examined so that confidence can be applied to depth of frost table estimates from WorldView-2 based on canopy characteristics. Discrete WorldView-2 pixels are related to depth to frost table (bands red, near infrared1,2)and canopy metrics/topography obtained from airborne LiDAR. Variability is due, in part to absorption of near infrared by shadow fractions observed within WorldView-2pixels, and spectral reflectance of ground vegetation visible within mixed pixels. High resolution spectral imagery, therefore, provides a link to processes controlling spatial variability of the depth to frost table.

Using high density ALS data in plot level estimation of the defoliation by the Common pine sawfly

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The climate change has been related to the increase of forest insect damages in the boreal zone. The prediction of the changes in the distribution of insect-caused forest damages has become a topical issue. The common pine sawfly (*Diprion pini* L.) is regarded as a significant threat to boreal Scots pine (*Pinus sylvestris* L.) forests. Efficient and accurate methods are needed for monitoring and predicting changes in insect defoliation. In this study, the field work has been carried out in 2009 in Eastern Finland, where *D. pini* has caused considerable damage in managed Scots pine forests. Altogether 95 sampling plots were used in the analysis. A high density ALS data was acquired simultaneously with the field work. The aim of the present study was to test the accuracy of the plot level needle loss predictions determined from the area based and single tree ALS features separately. The Random Forest method (RF) was utilized in the estimation. The best classification accuracy for the test set was 67.4% (area based features). The best plot level accuracy using the tree-wise features was 60.6%, respectively.

Assessing spatial variation for tree and non-tree objects in a forest-tundra ecotone in airborne laser scanning data

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Changing climate is expected to have a significant impact on temperature-sensitive ecosystems like the forest-tundra ecotone. In Norway, this ecotone constitutes a large proportion of the total land area and effective monitoring techniques are required. It has been indicated that height and intensity data from airborne laser scanning may hold potential for monitoring of small trees. In the present study, Voronoi polygons and variograms were employed in order to assess the spatial patterns of trees and non-tree objects located in the forest-tundra ecotone. Patterns both for trees and non-tree objects could be recognised using Voronoi polygons in combination with height and intensity values. Furthermore, variograms and cross-variograms revealed different characteristics for trees and non-tree objects, however, limited to large individual objects located on flat terrain.

Exploring horizontal area-based metrics to discriminate the spatial pattern of trees using ALS

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Airborne Laser Scanning (ALS) data can be used to accurately determine tree and stand characteristics. We hypothesize here that three-dimensional ALS data can also be used for characterizing the horizontal forest structure like the spatial pattern of trees. This kind of information is of primary interest in forest management. The objectives of this study were (1) to identify ALS point cloud metrics and horizontal texture and landscape metrics, which can be used to determine the spatial pattern of trees and (2) to study how well the clustered spatial pattern of trees can be separated from others. The field data consisted of 28 microstands, of which 11 were clustered and 17 random or regular. Linear discriminant analysis was used to classify the microstands by means of the metrics calculated from ALS data. The best ALS metrics to determine the spatial pattern of trees were determined by the best overall accuracies (OA) and kappa-values (k) and based on the significance tests of models and the correlation matrices of metrics.
The classification of the spatial pattern of trees succeeds well based on ALS metrics, with the overall accuracy being 0.89 and kappa-value 0.77. Especially the calculated landscape metrics were found good predictors of

the spatial pattern of trees, for example: the number of the ground patches per hectare, the average size of the tree patches and the standard deviations of the size of all patches in the microstand. To conclude, our results were encouraging to detect the spatial pattern of trees based on low density ALS data.

Comparison of discrete return and waveform airborne LiDAR derived estimates of fractional cover in an Australian savanna

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The advance of commercial airborne lidar systems from discrete-return to waveform recording instruments has made repeatable estimates of biophysical variables from these different methods questionable. Using an experimental airborne waveform lidar data set acquired in an Australian savanna, this study presents a method for the derivation of canopy/ground backscatter coefficients from waveform lidar and a comparison of discrete return and waveform approaches to the estimation of fractional cover. Despite limited validation, the results indicate that waveform estimates of fractional cover can provide consistently higher accuracy than discrete return estimates under varying survey properties. Ongoing work using raw waveform data across larger areas and 3D radiative transfer simulations aims to develop a quantitative understanding of the impact of disparate sensor and survey properties on the detection of change in vegetation structure using commercial lidar instruments.

Notes:

Lidar-plots: A new wide-area data collection opportunity

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Forests are an important global resource, playing key environmental and economic roles. Forest monitoring and reporting are typically a national responsibility, with international collaboration and cooperation enabling generation of global statistics. The implementation of quality national monitoring programs is required for the generation of robust national statistics. Programs based upon samples of field plots have proven robust, but are difficult and costly to implement and maintain. Programs with air photo plot based sampling have been developed to mitigate some of the difficulties and limitations with ground plot based programs, especially for large nations. Further, samples of satellite data are becoming increasingly used to produce reliable statistics on forest characteristics and change over large areas. Photo- and satellite-based programs require ground measures to assist in ensuring the quality of attribution undertaken; thereby a conundrum emerges, where ground plots are again desired. To offer a source of detailed data for calibration and validation to large area mapping and monitoring programs we propose the collection and integration of lidar-plots. Light detection and ranging (lidar) has been shown as a data source offering timely and accurate measures of vertical forest structure, relating important information such as canopy height and biomass. Rather than using lidar to produce wall-to-wall coverage we propose the use of transects of scanning lidar to relate the forest conditions present over large areas. Given appropriate sampling statistics can be generated directly from the lidar-plots collected over the transects. In other instances the lidar-plots may be treated as ground plots are typically treated, providing locally relevant information that can be used independently or integrated with other data sources. Issues such as costs and access limitations combine to result in ground plots being endemically in short supply. Lidar-plots are envisioned to mitigate this limitation and to produce information to aid and augment monitoring programs and to support science activities.

In this presentation we further outline the context resulting in the need for detailed forest information over wide areas, we describe the concept for specification, collection, and sharing of lidar-plots; a case study is then presented to illustrate the concept. We conclude with recommendations for alternate implementations, future activities, and improvements to the concept and processes described.

Notes:

Airborne lidar sampling of the Canadian boreal forest: Planning, execution & initial processing

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During the summer of 2010, a transcontinental aerial survey mission was performed to acquire 24,000 line km of lidar transects covering >15,000 km2representing all ecozones within Canada's boreal forest. The coverage equates to ~21 million 'lidar plots' at the 25 m grid cell resolution. Each 'plot' contains the position and intensity of 1000 to 2000 laser points, which describe the terrain surface and 3D canopy structure, which will be used to predict forest inventory attributes and to support calibration of wide area satellite-based imagery. Furthermore, in similar fashion to geo-located permanent sample plots, the lidar transect flight path from 2010can be re-surveyed in the future to facilitate monitoring of forest development and change in a consistent and quantifiable manner. The paper describes the mission planning criteria, survey logistical considerations and customised transect data processing routines.

Assessing the accuracy of GLAS topography estimation by using airborne Light Detection And Ranging (LiDAR) measurements

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Geography Department, the University of Cambridge, UK

Topography estimation is a key factor in forestry studies. The accurate prediction of topography underneath tree canopies will certainly improve the subsequent forest bio-physical characteristics estimation such as tree height, stem volume, biomass/carbon stocks. Thus, the assessment of the accuracy of GLAS topographical estimation is essential before the data can be used for forest bio-physical characteristics prediction. This study proposes the use of airborne LiDAR measurements to assess GLAS ground elevation estimates in a mixed woodland and arable site in south-east England near Thetford, UK, at at 52.4N, 0.81E, given that airborne LiDAR measurements have already been validated using 'ground-truth' data. GLAS full waveforms are decomposed into up to six Gaussian modes and different indices, such as waveform centroid position (GLA14 position) and GLA01 last peak position, are calculated based on the peak positions of these Gaussian modes. Elevations estimated from these indices are compared with airborne LiDAR elevation estimates for assessment purpose and optimal estimates will be selected based on the results.
Four comparison models are introduced in this study. From these, model 1 (the comparison between GLA14 elevation and non-filtered airborne last return pulses elevation) and model 4 (the comparison between GLA01 last mode elevation and filtered airborne last return pulses elevation) have the best performance with R-squared values of 0.89 and 0.87, respectively, and RMSE values of 3.82 and 4.69, respectively. After removal of outliers for model 4, the R-squared value improves to 0.99 and the RMSE value reduced significantly to 0.66.
A simplified experiment is implemented in this study in order to investigate the impacts on biomass/carbon stock estimates arising from use of different models, with the assumption that there is a uniform average tree height of 20 meters and uniform stem density through the study site.

Characteristics of satellite LiDAR waveform in tropical rain forests from the comparison with canopy condition derived from high resolution satellite data

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This study aims to investigate characteristics of satellite LiDAR waveform in tropical forests by comparing with canopy structure derived from high resolution satellite data. Study area is located in the Tangkulap Forest

Reserve, Sabah, Malaysia, which is managed by the Sabah Forestry Department under the Deramakot Forestry District. ICESat GLAS data for the study area were prepared and provided by the National Snow and Ice Data Center. GLA01data and GLA14 data were used. Footprints of laser pulse from ICESat GLAS were identified on the QuickBird image and stand structures in the footprints were estimated from crown information. First, canopy closure within a footprint was calculated using the generated mask. Distribution of individual crown areas within a footprint was investigated for all footprints in the study area. Grade of degradation due to historical selective logging was decided from these two factors, namely, canopy closure and crown size structure. Waveform in each footprint was extracted from ICESat GLAS data and the relationship between stand structure, which was estimated from crown information, and the waveform was investigated. In addition, waveform in oil palm plantation, which was outside of the extent of high resolution satellite data, was also investigated. The condition of the area was identified using using Google Earth. Stand structure was estimated from waveform of satellite LiDAR data. Length of waveform almost indicated maximum tree height. Peak position of waveform indicated the height of canopy layer. The height and position of peak of waveform indicated the grade of forest degradation. Further studies are required for identify the relationship between waveform of a shot of laser pulse from satellite LiDAR and canopy condition such as canopy closure and distribution of crown area quantitatively.

Model development for the estimation of aboveground biomass using a lidar-based sample of Canada's boreal forest

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The northern forested areas of Canada are largely unmanaged and not subject to inventories with the same level of detail or regularity as southern forested regions. In an effort to augment monitoring and inventory activities, airborne light detection and ranging (lidar) has been employed to obtain plot-level information over a sample of Canada's northern forests. During the summer of 2010, a series of 34 transects were flown over a total length of more than 24,000 km, spanning the width of the Canadian landmass from Nova Scotia to the Yukon, and crossing eight ecozones and 13 UTM zones. Following data acquisition, a suite of plot-level lidar vegetation metrics were calculated. To develop estimates of forest attributes such as biomass, however, field data were required from the range of conditions found across the region. To that end, datasets were acquired from Quebec, Ontario and the Northwest Territories. In this paper we describe the development of regression models for large area estimates of various tree aboveground biomass components using field and lidar datasets of uncommon provenance, with significant differences both in terms of the environments in which they were collected, and the characteristics of the field and lidar surveys. The equations developed are deemed suitable for application and extrapolation across the national series of lidar transects.

Notes:

Early assessment of industrial needs: harvesting and allocation decisions supported by ALS and TLS

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Context: To plan their own supply with regard to product demand, the wood industry needs precise requirements towards the qualitative properties of its purchased logs (volume, species, dimension, length, diameter, knottiness, taper, sweep and the absence of stem defects). Early information of the prospective wood quality from the designated harvestable stands is therefore required. Traditional inventory data are in most cases out-dated and not detailed enough to fulfil these information needs. In many forests (e.g. small private holdings) inventory data do not exist at all. To conduct up-to-date pre-harvest ground inventory is time consuming and costly. In this situation remote sensing with laser technology is a promising alternative.
Methodology: Aerial laser scanning (ALS) covers big areas and provides primarily height data, from where terrain information as well as canopy information can be extracted, so that single tree recognition and modelling of the crown shape is possible. Broadleaved and coniferous trees can be distinguished, but species identification is still difficult (Spectral aerial photography may help to solve this problem). From the tree height and the crown shape, important quality information like branchiness can be derived based on well established allometric functions, but information (diameter, shape, bark features) of the stem below the crown (which represents the most valuable part of the tree) is difficult to obtain via ALS.
Terrestrial Laser Scanning (TLS) provides information on the below-crown part of the stand. Depending on the type of laser scanner and the stand density, within a circle with a radius of r~±15m the exact position and detailed dimension and quality data of every (visible) stem can be obtained already with one instrument set up. Theoretically, a total coverage of the stand would be possible, with a sufficient number of instrument set ups, but this would not be economically feasible for industrial application.
The suggested solution is a combination of total (crown-) assessment via ALS and sampling of stem data via TLS. After AL scanning of the respective stand, circular sample plots are defined and located. Number and radius of the plots are derived from stand characteristics (variation of stand density and tree heights) based on statistical considerations. For all merchantable trees within these circular plots, their (foot) position and crown shape is 3-D modelled from ALS points.TL scanning of the stem of all (merchantable) trees is then conducted from the centre of these sample plots. Georeferenced data of ALS and TLS positions allow modelling the full tree by composing the respective crown and stem data.

Remotely sensed crown structure as an indicator of wood quality: A comparison of metrics from aerial and terrestrial laser scanning

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Aerial LiDAR offers a fast and efficient means to estimate wood quantity, but there has been little work to date on wood quality. In this study we investigate the hypothesis that remotely sensed crown structure from Aerial Laser Scanning (ALS) can be used as an indicator of log quality at an individual tree level.
A New Zealand *Pinus radiata* forest was flown with aerial LiDAR at 8 pts per m2. Five trees from within the forest were scanned with a terrestrial laser scanner (TLS) to determine external signs of log quality. These measurements were diameter at breast height (DBH), volume, taper, sweep, lean, circularity and average internode distance. In this study we develop a series of metrics from ALS point clouds for each tree to describe the crown structure, which are then correlated against the TLS data. To derive these metrics, novel algorithms were developed for TLS data which extend the level of detail previously obtainable. These algorithms are also detailed in this paper.
As only five trees were studied, the results are proof-of-concept more than outright proofs. The purpose of this paper is to document techniques which will be employed in the future over a much greater sample, proving the preliminary findings presented here. In this small sample we found that crown area from ALS had a moderately strong correlation with DBH and sweep. Crown density from ALS was also moderately correlated to average internode distance. The correlations show that there is at least a moderate connection between

crown structure and log properties, and that at higher LiDAR pulse densities and a larger sample size we can expect to describe this connection with greater certainty.
In further studies we also hope to correlate ALS and TLS metrics with internal wood properties, as found from destructive sampling.

Developing lidar interpretation software for wood resource inventory in Forests NSW

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Forest inventory programs are traditionally based on very limited field sampling data which is then extrapolated across the entire forest estate. One of the major weaknesses of this approach is that the limited number of plots often covers less than 2% of the total forest area and this can influence how representative the data may be of forest variation. Instead of relying solely on field plots sampled at around 1 per 400 to 1000 ha, future resource inventory programs could utilise high sampling density full-waveform lidar to conduct on-screen manual interpretation. The premise is that one analyst using lidar full-waveform data onscreen could potentially manually interpret 50 lidar plots per day compared to two field crewmembers measuring 4 to 6 plots per day. This involves a paradigm shift from 100% field survey dependent forest sampling to a mix of lidar plot interpretation with significantly fewer field plot samples. If feasible, this innovative resource assessment approach has the potential to provide significant savings in future resource inventory programs. The strength of the new generation of full waveform lidar systems lies in the enormous amount of structural data that can be rapidly collected. However, this strength is also their weakness for two reasons. Firstly, these systems generate extremely large volumes of data that demand exceptional data storage capacity (i.e. terabytes of space). And secondly, there is a scarcity of commercial software capable of processing the data in a way customised specifically for forestry purposes. Forests NSW (FNSW) and the University of New South Wales (UNSW) have developed a new lidar processing platform that offers the visualisation of point cloud data viewed in 2D and 3D displays and a suite of manual tools to add markers, measure stem and crown parameters and tag key attributes such as form quality, species and growth stage for each tree. In addition, a series of automated plot statistics can also be extracted such as point percentile counts at nominate height thresholds, common descriptive statistics (e.g. max, mean, mode, median, standard deviation etc.), and canopy cover percentage. A prototype of the new software should be ready for field testing in late 2011.

Towards automated and operational forest inventories with T-Lidar

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Forest inventory automation has become a major issue in forestry. The complexity of the segmentation of 3D point cloud is due to mutual occlusion between trees, other vegetation, or branches. That is why, the applications done until now are limited to the estimation of the DBH (Diameter at Breast Height), the tree height and density estimation. Furthermore other parameters could also be detected, such as volume or species of trees (Reulke and Haala)...
This paper presents an effective approach for automatic detection, isolation of trees and DBH estimation. Tree isolation is achieved using an innovative approach based on a clustering methodology followed by a skeletonization step. The DBH of trees is then determined automatically. The efficiency of our algorithm is evaluated with comparison with ground data, measured by classical methods.

3-D modelling of forest structure for parameterization of radiative transfer models

Martin Van Leeuwen*, Nicholas Coops, Glenn Newnham, Thomas Hilker, Darius Culvenor, Michael Wulder

Reconstructions of individual trees and their complex canopy structure provide an important means for studying a range of physiological processes including photosynthesis, respiration and resource use efficiencies and for assessing the effects of competition and crown structure on tree functioning.
However, measuring and registering detailed descriptions of tree and canopy structure has for long been challenging due to the laborious nature of data acquisition and subjectivity of taking field measurements in complex forest scenes. This study investigates the potential of ground-based, time-of-flight laser scanners for use in the 3D explicit reconstruction of forest structure and parametrization of radiative transfer models.

Evaluation of nonlinear equations for predicting diameter from tree height for Pinus radiata (D. Don) in an airborne laser scanning-based plantation inventory

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More than 30 height-diameter equations in the forest biometrics literature were evaluated to select candidates for deriving equation forms for predicting diameter from tree height in support of LiDAR based forest inventory. The evaluation was based on four criteria: (1) the height-diameter function is inversable, (2) the inverse function is continuous and monotonically increasing over a specified working range of total tree height, (3) DBH is equal to zero at breast height in the inverse function, and preferably (4) the inverse function has an inflection point that is consistent with biological expectations. A total of 12 candidate equation forms were derived, which included 5 two-parameter and 7 three-parameter equations. The estimation properties and predictive performance of these 12 equation forms were further evaluated and compared through repeated sampling and fitting using data from 3581 trees destructively sampled for taper measurements from *Pinus radiata* plantations across New South Wales, Australia. Three equation forms, including the constrained Richards, Weibull and the combined power and exponential function, displayed superior prediction accuracy and estimation properties, and so were recommended as the primary equation forms for developing diameter-height equations. The remaining equation forms were marred by either lower prediction accuracy or poorer estimation properties or both. The three recommended equation forms should only serve as basic deterministic specifications, upon which other tree and stand variables should be incorporated as predictors to further improve their predictive performance.

Revisiting the status of space-borne lidar missions for assessing structural and biophysical forest parameters in the context of sustainable management of Earth resources

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Assessing forest aboveground biomass at global scale is crucial to address the challenge of sustainable management of forest resources and to strengthen forest-based climate change mitigation. To achieve this goal relying on spaceborne lidar missions is acknowledged to be a highly relevant solution. However, if this is taken as a given from the measurement point of view, the premise that spaceborne observation is the most suitable solution to provide information for sustainable management of forest resources is worth discussing. In this paper we suggest to take a fresh look at measurement processes designed to support the monitoring of Earth resources. We discuss the sustainability of Earth observation from space considering (1) issues that call into question the assumption that Earth-orbiting platform will always be available to the civilian remote

sensing community and (2) issues concerning environmental impacts of space activity on the Earth. This leads us to suggest some actions that could help to design future observation systems in a more sustainable way in order to strengthen the capacity of measurement processes to meet their stated functional goal, i.e. sustainable management of forest resources.

Vegetation classification in the Swedish sub-arctic using a combination of optical satellite images and airborne laser scanner data

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The aim of this pilot study was to investigate to which degree the accuracy of automated vegetation classification in the Swedish sub-arctic could be improved by combining optical satellite data with airborne laser scanner (ALS) data, compared to using satellite data only. This information is of interest in an ongoing discussion about the possible inclusion of the mountains in northern Sweden in the national laser scanning that started in 2009. A SPOT 4 scene and ALS data from an Optech ALTM Gemini scanner, both from 2010, were used in maximum likelihood classification. Data for training and validation was obtained from 279 plots with 20 m radius that were visited in field 2010. These plots were located near Abisko in northern Sweden (lat. 68° 23' N, long. 18° 53' E), on the north and south side of Lake Torne Träsk. A classification scheme with 7 classes based on the Swedish mountain vegetation map was used. Classification using only SPOT data gave an over-all accuracy of 75.6%, and the combination of SPOT data and ALS data increased the accuracy to 81.4%.

Lidar data and cooperative research at Panther Creek, Oregon

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A 2,300 hectare forested watershed in the coastal mountain range of Oregon, USA is the subject of collaborative research with a principal objective of evaluating uses of lidar and other remotely sensed data for the development of detailed forest inventories. Panther Creek watershed (4518’ N, 12321’ W) is at an elevation of 100-700 m, about 57 km southeast of Portland. Major species are Douglas fir, western hemlock, western red cedar, grand fir, red alder and big leaf maple; tree heights are up to 60 m. The Bureau of Land Management and other cooperators are using the watershed to test and develop methodology for detailed stand level forest inventories, the detailed mapping of soils and slope stability, and the assessment of other ecosystem functions. Wall-to-wall discrete return lidar has been acquired under leaf-off conditions annually starting in 2007, and will continue through 2012. Leaf-on discrete return lidar was collected in 2007 and 2010 and will be collected in 2012. Surveys used Leica ALS50 Phase II or ALS60 lasers; pulse density is about 8 per m2; in 2010 selected areas received multiple passes, raising the density up to 50 pulses per m2. Return intensities are being corrected for power output and camera-to-target distances. Full waveform lidar leaf-on data was acquired in 2010, as was 4-band color-infrared imagery using a Leica ADS40 camera. Also in 2010, hyperspectral data from a Hymap sensor was acquired. Eighty-four cadastral-surveyed 0.08 ha stem-mapped permanent plots were installed, mostly in 2009; measurement will be repeated after the 2012 growing season. Several other imagery sources are available. A project goal is to compare and evaluate methodologies. All data are available to research groups wanting to participate. Data are well documented and organized, and include cut-outs of the remotely sensed data at each of the plot locations.

LiDAR estimation of quadratic mean canopy height and stem density in native sclerophyll forests

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LiDAR, relatively a new active remote sensing technology, capable of providing three-dimensional structural information of forest stands as well as individual trees has already been established as an operational tool in European and North American forestry. LiDAR estimates of various structural and biophysical parameters are

more accurate for pine forests than that for the broad-leaved and mixed species multi-story forests. In this study, plot level mean dominant height and quadratic mean canopy height were estimated quite accurately using the LiDAR data from two different types of native sclerophyll forests. R^2 of the regression model for the mean dominant height was 87.09 % for the Central Highlands Ash Regrowth (CHAR) and 92.1 % for the Black Range Mixed Species (BRMS) forest. Similarly, R^2 of the regression model for the quadratic mean canopy height was 48.4 % for the CHAR and 92.7 % for the BRMS forest. Stem density (number of trees per hectare) is the most difficult forestry attribute to estimate from remote sensing technology including LiDAR. When various LiDAR metrics were used directly to develop a regression model of stem density in the CHAR and BRMS forests, the models developed had very low (less than 0.3) R^2. Therefore, in this study, an indirect method of estimating stem density using LiDAR data was developed. Using this new indirect method, the number of trees was predicted with mean prediction error of -64.12 trees per hectare for calibration plots and 105.29 trees per hectare for validation plots in CHAR forest, which is a wet sclerophyll forest. In the RRMS forest, which represents a dry sclerophyll forests, prediction error for number of trees, was 79.99 trees per hectare for calibration plots and 4.96 trees per hectare for validation plots.

Using a flux footprint model and airborne LiDAR to characterize vegetation structure and topography frequently sampled by Eddy Covariance: Implications for MODIS product validation

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Exchanges of CO2 transported to eddy covariance instruments are often assumed to be representative of site average vegetation, understory, and topographical characteristics, regardless of the frequency with which these have been sampled. All sites have some degree of heterogeneity (e.g. an upland area, bog, area of dense understory, etc.), which could influence CO2 exchanges if scalar fluxes from prevailing wind directions frequently sample these parts more than others. This could have implications for site representation, model evaluation, and remote sensing product validation and scaling. The use of flux footprint models has improved our understanding of the spatial and temporal distribution of source/sink areas measured within the field of view of eddy covariance instrumentation (e.g. Schmid, 1994). The flux footprint is defined as the probability of flux contribution per unit area upwind of the eddy covariance instrumentation (Kljun *et al.* 2002, 2004). When a footprint is combined with remote sensing data, the probability density function of the weighted source/sink contribution to the eddy covariance instrumentation provides spatially contiguous information on vegetation structural and topographic influences on net ecosystem production(NEP) (Chasmer *et al.* 2008). Simple logic follows: if CO2 fluxes originate from areas of higher biomass, then measurements of flux should indicate increased uptake (NEP) when compared with lower biomass areas (etc.), all else being equal. Combining footprints with high resolution spatially continuous remote sensing data from airborne LiDAR, hyperspectral or spectral imagery provides a powerful tool for characterizing the areas sampled most frequently by eddy covariance. In this study, we use a 3D classification methodology to characterize vegetation structural and topographic attributes most frequently sampled by eddy covariance within 1) a homogeneous mature boreal aspen stand; and 2) a heterogeneous upland aspen/wetland complex using airborne LiDAR. The vegetation and topographic characteristics found within the areas most sampled at each site were then used to classify the larger region for evaluation of the MODIS gross primary production (GPP) product, i.e. choosing MODIS pixels that have similar attributes to those found within footprint most frequently sampled by eddy covariance.
The results of this study find that footprints from prevailing wind directions at the homogeneous mature aspen stand have, on average, taller trees (7%), greater effective LAI (30%), denser understory (5%), and fewer low-lying topographic depressions than secondary wind origins. At the heterogeneous aspen stand, footprints from prevailing wind directions have, on average, shorter trees (-11%), lower effective LAI (-17%), and a greater proportion of topographic depressions.

Classification of vegetation structure and topography within a 1 km radius of the homogeneous and heterogeneous stands indicated that 56% (homogeneous aspen) and 69% (heterogeneous aspen) were representative of vegetation and topographic attributes sampled by eddy covariance. Thus, prevailing wind directions may over- or under-sample some parts of the ecosystem more than others, which could result in over- or underestimates of NEP when compared with similar representative ecosystems.

When scaled to MODIS GPP, correspondence with GPP estimated using eddy covariance and meteorological methods improved by 13% when using LiDAR 'classified' pixels as opposed to those pixels most proximal to the tower. This illustrates that airborne LiDAR and footprint analysis can be used to link eddy covariance measurements of ecosystem exchanges between scales. This has important implications for assessment of spatial variability of vegetation/topography on NEP; identifying landscape features that are frequently sampled; classifying spatial heterogeneity; and scaling. More detail of this study is provided in Chasmer *et al.* (2011).

Satellite vs. airborne lidar estimates of aboveground biomass and forest structure metrics at footprint scale

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Small footprint airborne lidar, sometimes referred to as airborne laser scanning (ALS), provides the best measurement accuracy of terrain elevation and vegetation heights, even on sloped terrain or for dense forests. However, large footprint, full waveform satellite lidar data, such as data provided by the Geoscience Laser Altimeter System (GLAS) aboard the Ice Cloud and land Elevation Satellite (ICESat), proved to have the potential for assessing vegetation parameters at unprecedented scales, from regional to continental and global extents. The overall goal of this study was to compare biomass estimates and height metrics obtained by processing GLAS waveform data and spatially coincident discrete-return airborne lidar data over forest conditions in east Texas, which are characteristics of much of the south-eastern United States. The study area includes pine plantations in various developmental stages, old growth pine stands, and upland and bottomland hardwoods. Since biomass estimates are derived from waveform height metrics, we also compared ground elevation measurements and canopy parameters. More specific objectives were to compare the following parameters derived from GLAS and airborne lidar: (1) ground elevations; (2) maximum canopy height; (3) average canopy height; (4) percentiles of canopy height; and (5) above ground biomass. We used the elliptical shape of GLAS footprints to extract canopy height metrics and biomass estimates derived from airborne lidar. Individual tree parameters, including tree height, crown width and tree locations, were estimated from the ALS-derived canopy height model using an individual-tree isolation method and were related to diameter-at-breast-height (dbh) measurements and dbh-based general biomass equations for pine and mixed hardwood to compute above-ground biomass. The resultant biomass map derived at individual tree level was used as the dependent variable in our investigations of deriving biomass at footprint scale using GLAS variables and linear regression models.
Results indicated a very strong correlation for terrain elevations between GLAS and airborne lidar, with an r value of 0.98 and a root mean square error of 0.78 m. GLAS height variables were able to explain 80% of the variance associated with the reference biomass derived from airborne lidar, with an RMSE of 37.7 Mg/ha. Most of the models comparing GLAS and airborne lidar height metrics had R-square values above 0.9.

The significance of managed and natural vegetation on house survival during wildfires

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The impact of wildfires at the urban interface is a major concern for people safety and property loss. The Australian forest fires of February 2009 resulted in the highest loss of life from forest fires in Australian history, and occurred in semi-rural and rural areas in Victoria. The most deadly of these fires occurred in the Kinglake region north of Melbourne. In this area there is generally no clear delineation of the urban interface. In this situation, where houses can be located within the natural forest, each house has its own unique forest boundary which must be defended in the event of a fire. Along with the natural forest, there are also small forest patches and isolated trees between houses and the forest that may provide a direct fuel path to the house for the flame front. These patches of vegetation are typically assumed to be 'managed' vegetation; areas from within which fire fighters can carry out suppression activities safely and effectively. In this study Lidar data collected prior to the fire was used to generate maps of vegetation extent using a cover threshold method. Spatial patterns of vegetation extent were then used to discriminate managed vegetation from natural forest, and the managed vegetation around each house was then analysed with respect to the damage that each house experienced from the wildfire. The results showed that the proximity of managed vegetation to houses was not a significant factor in relation to fire damage, but that the total cover of this vegetation around the house was a significant factor.

Notes:

Looking forward to lidar's colourful future

Iain Woodhouse

The University of Edinburgh and cArbomap

In this presentation, Dr Woodhouse will present a vision for multi- and hyper-spectral canopy lidar from aircraft and satellites.
It will describe results of a 2008 laboratory-based experiment that demonstrated the principle of our multispectral canopy lidar concept, measuring the normalised difference vegetation index (NDVI) and the photochemical reflection index (PRI) of potted trees, and a new experiment in 2011 being developed with Heriot Watt University to look at hyperspectral canopy lidar.
The presentation will also describe a design for an airborne Multi Spectral Canopy LiDAR (MSCL) system that operates at four wavelengths, as opposed to the existing commercially available single wavelength LiDAR systems. This instrument is being optimised to measure forest properties by combining the proven strengths of multispectral sensing with the 3D structural information from LiDAR. The value of multispectral lidar is that it:
> uses the spectral information to better resolve 3D forest structure (including the location of the ground), and
> determines those processes directly related to photosynthesis and the uptake of carbon throughout the canopy (traditional spectral imagers can only measure the top layer of the canopy that is visible from above).
Finally, Dr Woodhouse will present a vision which will see this unique approach taken into space so that all the world's forest carbon can be mapped. This would give an unprecedented level of information that would allow us to better manage the global forest resource. The spaceborne concept is called SpeCL (multi-Spectral Canopy Lidar, “speckle”). In 2010 it was submitted as a full application to the European Space Agency’s Earth Explorer 8 call and it was highlighted in a short list of 11 mission that have "considerable scientific potential". The ESA Scientific Advisory Committee described the approach as a "very innovative mission concept".

Notes:

Error assessment and mitigation for hyper-temporal UAV-borne LiDAR surveys of forest inventory.

Luke Wallace*, Arko Lucieer, Darren Turner, Christopher Watson

School of Geography and Environmental Studies, University of Tasmania

Remotely sensed LiDAR data has become an important tool in the management of modern forest inventories. Monitoring the high frequency changes within forests with this data has been restricted by the cost and intermittent nature of LiDAR surveys. The use of Unmanned Aerial Vehicles (UAVs) as a remote sensing platform is a rapidly developing field and is capable of allowing highly dynamic environmental changes to be monitored. As such recent studies presented in the literature highlight the potential of UAV systems for forest monitoring. This study further investigates the potential of UAVs by examining the achievable accuracy of a newly developed UAV-borne LiDAR system in comparison to a traditional full scale system. The major contributions to the error budget of a UAV-borne LiDAR system are constrained through the use of a novel UAV specific processing workflow. Central to this workflow is the fusion of observations from a low cost Inertial Measurement Unit, a GPS receiver and a high definition video camera with a Sigma-Point Kalman Smoother allowing for highly accurate estimates of orientation. We found that using this workflow and under certain flying conditions accuracies similar to a modern full-scale system are achievable from this low-cost platform.

A new photon counting lidar system for vegetation analysis

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This paper considers the potential of a new scanning photon-counting system for vegetation analysis. The 3D Mapper sensor was developed by Sigma Space Corporation and is being tested within NASA's Carbon Monitoring System (CMS) project (NASA, 2010). The sensor is able to map 60 km2 per hour using less than 150 mW of 532 nm green light with about 30 cm between measurement points. While this area coverage rate is already several orders of magnitude higher than can be achieved by conventional lidar, substitution of higher power lasers would permit significantly higher mapping rates with the same resolution or much higher spatial resolution at the current rates. Data were collected for a test site to the west of Fredericksburg, Virginia, USA and demonstrated the capability with a low powered laser, of relatively high density data collection, and good penetration through the canopy, despite high canopy fractional cover and a hazy atmosphere at the time of flight. This preliminary study supports the potential of this emerging technology for vegetation analysis. Further research is required to develop algorithms to exploit the capabilities of such systems and to provide a greater understanding of the interactions with vegetated surfaces. Studies of this nature will inform future photon-counting satellite lidar sensors such as NASA's ICESat II, which is due for launch at the beginning of 2016.

Sorted Pulse Data (SPD) Format: A new file structure for storing and processing LiDAR data.

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This paper presents a new generic method and format for storing and processing airborne and terrestrial LiDAR pulse data within a HDF5 file. The format is specifically designed to support both traditional discrete return and full waveform data, uses a pulse (rather than point) based data model and has been developed and applied successfully using a wide range of disparate airborne and terrestrial LiDAR datasets. The format is proposed as an alternative to existing solutions as it includes support for full waveform data, explicit pulse based data structures and flexible spatial indexing using cartesian, spherical and polar coordinate systems and projections. The HDF5 format supports compression but in part due to the more complex data structures

used the amount of compression that can be achieved is limited. However, it compares favourably with the file size of uncompressed LAS files and is able to accommodate a much wider range of LiDAR datasets.

Tree detection, delineation, and measurement from LiDAR point clouds using RANSAC

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As Light Detection And Ranging (LiDAR) (point) data sets increase in resolution, earth scientists become more interested in detecting and delineating trees using LiDAR. The majority of conventional methods that detect and delineate trees convert point data into gridded surfaces. Unfortunately, this conversion process has the potential to introduce error. We improve a point-based geometric model fitting strategy based on "RANdom Sample Consensus" (RANSAC), known as *StarSac*, and compare the method's results against field data. The analysis demonstrates that *StarSac* produces similar results to field data, and is a strong alternative to conventional methods.

Mobile terrestrial laser scanning in urban tree inventory

Mikko Vastaranta [1], Tuula Kantola* [1], Markus Holopainen [1], Ville Kankare [1], Harri Kaartinen [2], Antero Kukko [2], Matti Vaaja [3], Juha Hyyppä [2], Hanna Hyyppä [3]
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In this study we evaluated an accuracy of mobile terrestrial laser scanning (MLS) measurements in urban tree inventory. The MLS data were collected in August 2010 with the FGI Roamer mobile mapping system, consisting of a Faro LS 880 laser scanner and a NovAtel HG1700 SPAN58 INS system mounted in a car. Study areas were divided to park and urban forest located in Seurasaari, Helsinki, Finland. Studied inventory characteristics were tree location and –diameter-at-breast-height (*dbh*). Reference measurements consisted altogether from 201 trees, which locations were measured using RTK GPS and static terrestrial laser scanning while tree *dbh*s were measured using steel callipers. Tree mapping and *dbh* measurements were done from the MLS point clouds manually. Tree location accuracy of MLS measurements were 0.72 m in park and 0.47 cm in forest conditions as root mean squared error in *dbh* were 7.0% and 12.5%, respectively. MLS can be used in urban tree inventory in targets with a good visibility and relatively dense network of roads or paths.

Notes:

Another dimension from LiDAR - Obtaining foliage density from full waveform data

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LiDAR tells the user *where* surfaces are, not *what* they are. In this study we investigate the potential for waveform LiDAR to provide more information on the nature of the returns over forestry. Waveform LiDAR was acquired for ten *Pinus radiata* plots in a New Zealand plantation, along with comprehensive leaf area sampling in 2m vertical bands. The decay rate of each waveform peak was shown to be a useful tool for estimating foliage density, and has potential for identifying regions containing ground and understorey. Leaf Area Density (LAD) is an expression of foliage density per unit height, and a relationship between waveform decay rate and LAD was developed with an R2 of 56%. Incorporating the proportion of discrete LiDAR that fell in that band (which itself has an R2 of 50%) improves this model to explain 69% of the variation in LAD. This is a good result, especially given the costs and difficulties in measuring leaf area directly. As foliage density varies dramatically on a fine scale it was not possible to differentiate the nature of every single LiDAR return – but by averaging over a small area local variation in LAD could be easily mapped. Ground returns could be distinguished as having short decays, and broad leafed understorey typically had values between those of the canopy and ground, although surface roughness and slope make it impossible to robustly identify single returns. This study produced a useful model for estimating LAD in *Pinus radiata* which could easily be extended to other coniferous species.

The Sorted Pulse Data Software Library (SPDLib): Open source tools for processing LiDAR data.

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SPDLib is a new set of tools that allow processing and analysis of the full range of LiDAR data from terrestrial, airborne and spaceborne systems, including both discrete return and waveform datasets. The software provides an implementation of the SPD file format that allows efficient and flexible storage of these datasets largely through the inclusion of spatial indexing and pulse (rather than point) based data structures. A visualisation tool (SPD Points Viewer), which builds on top of SPDLib and the SPD file format, has also been developed. The software and source code have recently been made freely available and can be accessed online through open source code repositories. Future developments will focus on the development of new waveform processing functionality and optimizing performance. The software and documentation can be obtained from http://www.spdlib.org.

Comparison of point cloud data reduction methods in single-scan TLS for finding tree stems in forest

Paula Litkey, Puttonen Eetu, Liang Xinlian*

Finnish Geodetic Institute

The point density in a single-scan terrestrial laser scanner (TLS) point cloud is very dense close to the scanner and gets sparser as the distance from the scanner increases. A full circular scan can contain tens of millions of points, which is impractical for most algorithms that work on point data. The number of points can be reduced by taking a sample of the original data. We have studied what influence different sampling methods have on the number of points that falls on tree stems. We propose that the number of points available on a far-away tree can be increased with a smart data reduction scheme. The data reduction favours far-away points over the densely located points close to the scanner. The main findings of this study are that removing ground points before sampling gives a great advantage in data reduction and that a point selection using only horizontal distances (2D Cartesian, xy-plane) favours low points.

Automated log counting: Proof of concept algorithm

Hamish Marshall

Interpine Forestry Ltd

Improving log inventory is a key area where the New Zealand forestry industry could significant improve its supply chain performance. Although the process of counting logs seems relatively simple; in reality it is a difficult and labour intensive job. This is particularly significant to the New Zealand log export industry which is required to count and barcode every log (excluding pulp) that is exported. The fluctuating nature of export markets means that automated methods of counting logs hold significant potential. This paper investigates the accuracy of log counts for logs in pile/stacks using 3-dimensional (3D) point cloud data obtained from a ground based LiDAR scanner. In the past there have been a number of attempts to develop an automatic log counting system, the majority of these have used 2-dimensional photographic images. It was hypothesised that using 3D point data would overcome some of the problems that these approaches have encountered in the past. The validation study carried out on the algorithm showed that logs can be accurately counted and log diameters can be measured. Further work would be required to develop the algorithm into a commercial product and to determine the most cost effective hardware required to collect the 3-dimensional data required by the algorithm.

Optimal LiDAR gridding parameterization for effective leaf area estimation in the boreal forest Yukon Territory, Canada

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The increased availability of LiDAR-based forestry models raises questions about fundamental procedural steps undertaken before published models begin. The processing stage being investigated in this study is the parameterization of routines used for gridding inputs for forestry models. Grids are a valuable format for modelling as they organize scattered point clouds into manageable pixels for sophisticated processing. Our objective was to examine the effect of grid cell resolution and circular search radii for gridding on resulting leaf area index (LAI) data layers. LAI is employed in models at various scales and was therefore of interest for a range of study objectives. We generated 16 gridded estimates of LAI using unique combinations of cell resolution and search radius for comparison with values measured in the field. Our results determined that cell resolution was not important, allowing for more application flexibility without introducing bias, while search radius was critical for obtaining the most accurate estimates. This type of scale sensitivity analysis is important for any modelled variable that will be applied in a variety of spatial contexts.

Notes:

Developing a regional canopy fuels assessment strategy using multi-scale LiDAR

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Accurate assessments of canopy fuels are needed by fire scientists to understand fire behaviour and to predict future fire occurrence. A key descriptor for canopy fuels is canopy bulk density (CBD). CBD is closely linked to the structure of the canopy; therefore, lidar measurements are particularly well suited to assessments of CBD. LANDFIRE scientists are exploring methods to integrate airborne and spaceborne lidar datasets into a national mapping effort. In this study, airborne lidar, spaceborne lidar, and field data are used to map CBD in the Yukon Flats Eco region, with the airborne lidar serving as a bridge between the field data and the spaceborne observations. The field-based CBD was positively correlated with airborne lidar observations (R2 = 0.78). Mapped values of CBD using the airborne lidar dataset were significantly correlated with spaceborne lidar observations when analysed by forest type (R2 = 0.62, evergreen and R2 = 0.71, mixed). Though continued research is necessary to validate these results, they do support the feasibility of airborne and, most importantly, spaceborne lidar data for canopy fuels assessment.

LiDAR-based estimation of forest floor fuel loads using a novel distributional approach

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Light detection and ranging (LiDAR) has seen significant application across a range of forest structural assessment applications, ranging from forest volume and biomass assessment, to ecological applications such as leaf area and fuel load modelling. However, quantification of sub-canopy structure remains a challenge, especially when considering downed coarse woody debris (CWD) near the ground surface. This is true because the LiDAR signal attenuates through the canopy, LiDAR systems can be set to record the last of many returns, which is often the ground itself, and there is a system-specific vertical resolution that influences detection of structure in-between returns. We applied a LiDAR distributional approach to CWD modeling that included both above-ground and theoretical “below-ground” returns, with the latter being attributed to multiple scattering effects. This was done for oak dominant forests in central Appalachia, Kentucky, USA. Medium-fast (10h) and medium-slow (100h) CWD fuel loads exhibited the best results; e.g., an adjusted R2=0.99 and a root mean square error value of 0.111Mg/ha (4.7% of the mean) were achieved for 100h CWD fuel loads. Independent variables included a balanced set from both the above-and below-ground distributions. Results hint at the significant potential of extending distributional approaches to CWD estimation.

Using airborne survey to map stream form and Riparian vegetation characteristics across Victoria

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The State of Victoria has established the index of stream condition (ISC) methodology for providing a river health assessment. The index of stream condition (ISC) is a baseline dataset used in river investment and planning. The ISC evaluates the environmental conditions of the major rivers and tributaries across Victoria. The ISC assessment undertaken during 2009-2010 has included a significant investment in the use of LiDAR and aerial photography to assess the riparian vegetation and river form components of ISC stream network. The health of riparian vegetation and stream form is assessed by measuring a number of metrics. Each of the metrics can be measured by either or combination of LiDAR and/or aerial photography. The scores for all the ISC metrics are amalgamated into a single sub-index score for both the river form and riparian vegetation.

These sub-indexes will be combined with other sub-indices (such as hydrology and aquatic life) to provide an assessment of health for each river reach in Victoria.
Compared to the results from prior research, the preliminary results have shown that riparian vegetation and stream form metrics are measured with a significant increase in detail, coverage and accuracy from the previously available information. It should be noted that the products are still being tested and validated in various catchments across the state.
More significantly, the final results will provide a much needed input into the Victorian Strategy for River, Estuaries and Wetlands and more specifically will help to set management targets. The datasets will provide a key source of information for the regional priority setting process which identifies sites where on-ground works should be undertaken to either protect river values or to mitigate against risks to their values.

Full waveform LiDAR for assessment of river health

David Moore*, Alys Wall, Thomas Hollaus

The Murray-Darling Basin covers 1,000,000 square kilometres; 13% of the Australian continent and produces 39% of Australia's total agricultural output. However, thirteen of the Basin's 23 valleys are categorised as being in 'very poor' health and a further seven are in 'poor' health (Davies et al 2008). The Murray-Darling Basin Authority (MDBA) is responsible for reporting the health of the Basin's rivers and for this purpose established the Sustainable Rivers Audit (SRA) to collect and analyse data to determine the environmental condition of the rivers by objective and repeatable methods.
The first SRA assessed river health under three indicator themes; 1) Fish, 2) Macro invertebrates and 3) Hydrology. Two additional themes were included in the second SRA; Physical Form (of the river channels) and Vegetation. This project describes how these two additional themes were measured using full-waveform LiDAR. Highly automated workflows developed in the TNTmips™ Spatial Modelling Language were used to extract information from the LiDAR for statistical analysis. A semi-automated tool was developed to measure a range of river channel and foliage attributes by objective and repeatable means. More than 50 measurements are generated for each of 1610 sites stratified across the Basin's 23 river valleys. Extensive field survey was used to verify the accuracy of the data. Full waveform LiDAR represents an extremely rich source of environmental information. This was exploited by the Sustainable Rivers Audit (SRA) program as a means of measuring the geomorphology and riparian vegetation at 1610 sample sites widely scattered across the Murray-Darling Basin (MDB). The project methodology was highly innovative and required the development of new algorithms and processes to extract the required information from LiDAR point clouds.

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Deploying LiDAR applications - Gearing toward the potential of LiDAR application in Malaysian forestry

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Information on forest properties have grown over time and will continue crucially in the future. The focus on timber for commercial trade in early 1960's in Malaysia has been changed towards multi function forestry, supported by multi resources survey. Starting with high demand of the latest data and accurate information, and cost effective monitoring system, application of various technology of sensing system is applied into forestry. The introduction of precision forestry concept is not new but in Malaysia is still at infancy stage. It deals with advanced sensing technologies and analytical tools to support site-specific economic, environmental, and sustainable decision making for the forest management and development. The key discipline is highly relying on accurate, timely and detailed forest inventory characterization and structural information. This is possible by utilization of accurate measurement forestry data and information to improve operations and processes. Despite of the current use of high resolution satellite and airborne sensing, LiDAR is a promising alternative tool to be used in forestry sector. LiDAR can be used in forest engineering for terrain mapping and road planning, and tree/stand measurement for tropical forest. This paper gives a synopsis of LiDAR sensing technology application and its potential to Malaysian forestry.

Laser scanning by echo signal digitization and waveform processing

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LIDAR technology based on time-of-flight ranging with short laser pulses enables the acquisition of accurate and dense 3D data in form of so-called point clouds. The technique is employed from different platforms like stable tripods in terrestrial laser scanning or aircrafts, cars, and ships in airborne and mobile laser scanning. Historically, these instruments used analogue signal detection and processing schemes with the exception of instruments dedicated for scientific research projects or bathymetry. In 2004, a laser scanner device for commercial applications and for mass data production, the RIEGL LMS-Q560, was introduced to the market, making use of a radical alternative approach: digitizing the echo signals received by the instrument for every laser pulse and analysing these echo signals off-line in a so-called full waveform analysis in order to retrieve almost all information contained in the echo signal using transparent algorithms adaptable to specific applications. In the field of laser scanning the somewhat unspecific term "full waveform data" has since been established. We attempt a classification of the different types of the full waveform data found in the market. We discuss the challenges in echo digitization and waveform analysis from an instrument manufacturer's point of view. Furthermore, the benefits to be gained by using this technique, especially with respect to the multi-target capability of LIDAR instruments employing echo digitzation and the possibilities for applications in forestry assessment are addressed.

New methods and algorithms - Crown coverage calculation based on ALS data

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The objective of this paper is to present and evaluate a new geometrically unambiguously defined approach to calculate forest canopy cover, also known as crown coverage (CC) from airborne laser scanning (ALS) data based on national forest inventory (NFI) data. The CC is defined as the proportion of the forest floor covered by the vertical projection of the tree crowns. Most forest definitions lack in precise geometrical definitions for the calculation of CC and therefore, the results of common calculation methods differ and tend to be incomparable. To demonstrate the effect of such an unclear defined, common CC calculation method, CC maps, generated from moving window algorithms using different kernel shapes and sizes, are calculated and

analyzed for three study areas in Tyrol, Austria. The new unambiguous approach, the tree triples method, is based on defining CC as a relation between the sum of the crown areas of three neighbouring trees at a time and the area of their convex hull. The approach is applied for the same study areas and is compared with forest masks that are generated from moving window algorithms using different kernel shapes and sizes.

LiDAR estimation of quadratic mean canopy height and stem density in native sclerophyll forests

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LiDAR, relatively a new active remote sensing technology, capable of providing three-dimensional structural information of forest stands as well as individual trees has already been established as an operational tool in European and North American forestry. LiDAR estimates of various structural and biophysical parameters are more accurate for pine forests than that for the broad-leaved and mixed species multi-story forests. In this study, plot level mean dominant height and quadratic mean canopy height were estimated quite accurately using the LiDAR data from two different types of native sclerophyll forests. R2 of the regression model for the mean dominant height was 87.09 % for the Central Highlands Ash Regrowth (CHAR) and 92.1 % for the Black Range Mixed Species (BRMS) forest. Similarly, R2 of the regression model for the quadratic mean canopy height was 48.4 % for the CHAR and 92.7 % for the BRMS forest. Stem density (number of trees per hectare) is the most difficult forestry attribute to estimate from remote sensing technology including LiDAR. When various LiDAR metrics were used directly to develop a regression model of stem density in the CHAR and BRMS forests, the models developed had very low (less than 0.3) R2. Therefore, in this study, an indirect method of estimating stem density using LiDAR data was developed. Using this new indirect method, the number of trees was predicted with mean prediction error of -64.12 trees per hectare for calibration plots and 105.29 trees per hectare for validation plots in CHAR forest, which is a wet sclerophyll forest. In the RRMS forest, which represents a dry sclerophyll forests, prediction error for number of trees, was 79.99 trees per hectare for calibration plots and 4.96 trees per hectare for validation plots.

Modelling light conditions in forests using airborne laser scanning data

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The amount of available sunlight in vegetated areas is an important factor influencing species composition, plant morphology and natural succession. It is therefore a significant parameter in forestry, ecology and other sciences dealing with biodiversity relevant studies. Research indicates a strong correlation between the quality and quantity of sunlight and the vegetation structure, both in horizontal and vertical direction. Due to the high complexity and variability of the canopy architecture, continuous area-wide data collection of light conditions in the understorey is needed for accurate modelling of light transmission. However, conventional ground based measurement methods are pointwise and time consuming, therefore not feasible for data acquisition of large areas. The ability of small-footprint airborne laser scanning (ALS) to penetrate small canopy gaps makes this remote sensing method especially suitable for vegetation studies. Geometric information of the vegetation structure can be derived directly from the 3D point cloud. This allows for modelling of the distribution of sunlight-absorbing or intercepting parts of the foliage, which consequently cast shadows on the surrounding understorey vegetation or the ground. Light transmission through the canopy can therefore be described in a very direct way by employing this 3D structural information. In this paper a methodology for modelling light conditions in forests using ALS data is proposed. The approach is based on a modified version of photogrammetric monoplotting. The parallel sun rays from variable sun positions act as projection rays being traced through the 3D point cloud (i.e. laser echoes) that represents the canopy. A defined size is assigned to each individual laser echo which casts a shadow of the respective size and shape. Shadowed areas are then derived by intersecting these projection rays with a digital terrain model and by rasterizing the projected point cloud. By employing ALS data from different acquisition times (leaf-on and leaf-off) the influence of vegetation phenology is explored. The derived shadow raster maps describe where a shadow is cast and how many intercepting parts of the canopy contribute to it. Consequently, these maps provide an excellent input for modelling the amount of available sunlight in vegetated areas, considering canopy gaps in arbitrary directions and also the seasonal variability of vegetation. The first results show that ALS is a time- and cost- efficient means for area-wide analysis of sunlight condition for forest floors, as well as for different understorey layers.

Estimation of Leaf Area Index based on airborne laser scanning and imaging spectroscopy

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Airborne laser scanning has become an established method for deriving structural forest parameters like tree height, crown length or crown cover. While some parameters are easily retrieved with laser scanning data and imaging spectroscopy, others are not, - the reason for which are model and (ground-based) measurement uncertainties. This is especially true for the estimation of the Leaf Area Index, which practically only allows for indirect measurements in forest environments. Since (a) the LAI is an important input parameter for process-based forest growth models and (b) there is yet no clear preference for using laser scanning or imaging spectroscopy for its retrieval, unlike other structural forest parameters, this study compares the LAI estimation both from airborne laser scanning and imaging spectroscopy and discusses related difficulties.
During an extensive field campaign at one of the EnMAP (Environmental Mapping and Analysis Program) core forest research sites (Merzalben, Pfaelzerwald, Germany) in August 2010, a total of 25 plots in mixed beech-oak forest stands were sampled for LAI. A laser scanning dataset collected almost contemporarily to the HyMap image acquisition served for establishing fractional cover maps with two different methods (1). Corresponding LAI maps were generated based on the formulation proposed by Verger et al. (2) and according to the classic LAI formulation (3). The results were compared to the mean ground-based LAI of the 25 plots. To test the transferability of the LAI retrieval from laser scanning a comparison was made with a second laser scanning dataset from another forest region (4). The LAI retrieved from the laser scanning was then compared to LAI derived from empirical regressions with selected hyperspectral vegetation indices.
Results show that the individual empirical models all provide a good estimation of Leaf Area Index with R^2 values ranging from 0.50 to 0.92. By stratifying according to tree species and stand structure as well as adjusting the LAI-model applied to the laser scanning data, the performance of these empirical models can be greatly improved for both the laser scanning and the HyMap-based vegetation indices. However results also show that both approaches suffer equally from the main limitation of the empirical approach - which is the lack of transferability. For the laser scanning data the estimation is influenced by the combined effects of variable laser scanner system parameters and site-specific canopy variables such as clumping and leaf angle distribution. Further research is needed to assess these effects, particularly with regard to the different laser scanning based gap fraction models. For this purpose we will apply terrestrial laser scanning to validate both the airborne laser scanning derived gap fraction and the ground-based measurements.

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