LiDAR – A new tool for forest measurements?[1]

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ABSTRACT

LiDAR (Light Detection and Ranging) is a remote sensing technology with strong application potential in forest resource management. It provides high measurement precision that can be used for tree and stand measurements. Although LiDAR has not been used widely as an operational measurement tool, there is a significant body of research and a number of projects at Mississippi State University (MSU) that illustrate the potential for this technology to be incorporated into operational forest assessments. This paper provides basic background on the capabilities of LiDAR in a forest measurement context that illustrates specific examples of LiDAR use including: 1) individual tree assessments, 2) a forest inventory protocol currently being operationally tested, 3) forest structure analysis, and 4) forest typing.

Key words: LiDAR, remote sensing, tree identification, tree measurements, forest inventory, forest types

RÉSUMÉ

Le LiDAR (Light Detection and Ranging) représente une technologie de télédétection ayant un fort potentiel d'utilisation pour l'aménagement des ressources forestières. Elle procure une grande précision au niveau des données utilisées pour mesurer les arbres et les peuplements. Même si le LiDAR n'est pas utilisé à grande échelle en tant qu'outil de mesure opérationnel, on retrouve une composante de recherche intéressante et plusieurs projets à la Mississippi State University qui travaille sur le potentiel de cette technologie en matière d'évaluations forestières à l'échelle opérationnelle. Cet article illustre l'information de base sur les capacités du LiDAR dans un contexte dendrométrique au moyen d'exemples spécifiques de son utilisation : 1) pour évaluation d'arbres individuels, 2) pour un protocole d'inventaire forestier présentement sous essai opérationnel, 3) pour analyse de la structure forestière et 4) pour la cartographie des peuplements forestiers.

Mots clés : LiDAR, télédétection, identification des arbres, dendrométrie, inventaire forestier, peuplements forestiers

Introduction

Forested regions of the world, by the very nature of their size, complexity and remoteness, present significant challenges to detailed resource assessments. Forestry professionals have traditionally approached information needs by design and implementation of field surveys that utilize statistical sampling and summary techniques to characterize forest resources (Avery and Burkhart 2002). Increasing costs of field surveys, coupled with ever-increasing demands for collection of both timely and more detailed information, are directing resource professionals to consider significant changes in their approaches to forest assessments. Recent developments in remote sensing and allied geospatial information technologies offer new pathways by which foresters will likely conduct resource assessments in the 21st century. This paper addresses a relatively new remote sensing technology, LiDAR (Light Detection and Ranging), and its potential use in forest resource assessment.

Aerial photography has been in operational use for well over five decades and continues to be an important means by which resource managers evaluate forestlands. Measurements such as tree height, crown diameter, and stem density can be obtained from aerial photographs through time-consuming and labour-intensive photogrammetric processes. This often limits the use of aerial photography to rapidly assess forest resources over extensive areas. Environmental satellite data first became widely available with the advent of the Landsat program established by NASA in 1972 (Cohen and Goward 2004). The Landsat series of satellites can effectively image extensive areas, but due to spatial resolution and other system constraints, do not have the capability to provide for direct measurements such as tree heights (Hudak *et al.* 2002).

LiDAR systems have evolved to the point that they now represent an important new measurement capability for forest analysis. For the first time in the relatively short history of modern remote sensing, there now exists a system that can produce direct measurements of individual trees and stands. In this paper, we offer a short overview of LiDAR system characteristics and a background on this technology's use in forest assessments. It is not intended as an exhaustive review per se, as this could literally fill an entire book on the subject. Instead, through a combination of review of relevant litera-

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ture, coupled with specific examples of recent research at Mississippi State University (MSU), it attempts to qualify some of the potentials of LiDAR as a forest measurement tool.

LiDAR systems overview

LiDAR systems produce 3-D coordinate data based on laser ranging from an aircraft. Dubayah and Drake (2000) provided a brief overview of LiDAR use in forestry and described both large- and small-footprint system characteristics. Large-footprint LiDAR systems digitize the full returned energy waveform over a relatively large area (up to 25 m diameter) while small-footprint systems typically record the range of one or more discrete reflections from laser pulses that cover small areas (typically less than 1–2 m in diameter). Dubayah and Drake (2000) indicated that small-footprint systems may not be optimal for forestry due to reasons such as missed tree tops and lack of sufficient ground returns. They indicated that large-footprint systems were better for getting canopy height because the large footprint does not miss tree tops. It should be noted, however, that data from large-footprint systems are not generally suited to detection and measurement of individual trees and therefore, can not give a direct determination of relative stem density. With recent increases in the capabilities and deployment of commercial systems, focus on operational applications of LiDAR in the forestry sector has largely shifted to small-footprint systems. These systems not only provide good tree height information but also provide accurate terrain models, even under dense forest conditions (Kraus and Pfeifer 1998, Lee and Younan 2003, Reutebuch *et al.* 2003).

At the time of writing of this paper, there were no commercially operating large-footprint LiDAR systems although some were known to be under development. One must consider that in order for LiDAR to have operational use and marketability, there must be both proven applications and a significant demand to lead to corporate investment in the technology. Small-footprint LiDAR has been providing terrain models for a number of years as part of a viable commercial remote sensing sector (Hill *et al.* 2000, Renslow *et al.* 2000). One could readily assume, based on the existing commercial LiDAR sector and forestry applications that are documented throughout this paper, that small-footprint LiDAR will become a viable additional tool for resource assessments.

Typical commercial small-footprint LiDAR systems have been described by Baltsavias (1999). In general, these systems are composed of three distinct integrated components. The ranging device measures the time between each outgoing near-infrared laser pulse and its reflection back to the sensor in order to get direct distance (half travel time) to the target from the aircraft. Pulses are directed to the ground via a scanning system such that many pulses are transmitted and received across the flight path. A Differential Global Positioning System (DGPS) is used to fix the geographic position of the aircraft. An Inertial Measurement Unit (IMU) determines the three-axis orientation (angular roll, pitch, and yaw) of the aircraft. The processing solution to determine the geographic location of each LiDAR pulse reflection (sometimes referred to as a return) is made by mathematical integration of the range information in combination with the coordinate and angular measurements made by the system DGPS and IMU. This results in a set of points that give the horizontal and vertical position of each recorded LiDAR return in earth-referenced coordinates such as Universal Transverse Mercator Projection (UTM easting, northing, elevation in meters) or longitude, latitude and elevation.

The capabilities of LiDAR systems have seen remarkable improvements in recent years, particularly in the number of measurements taken per second. For example, Optech, Inc.[5] (www.optech.on.ca) is marketing a system that can acquire up to 100 000 measurements per second. Contrast this with systems reported as recently as five years ago (Baltsavias 1999) that typically generated from 5000 to 25 000 pulses per second. Most LiDAR systems in operation today have the ability to record multiple returns per pulse, and the return information often includes the relative intensity of these reflections. With the ability to vary the scan angle, scan frequency, and operating altitude, these systems can be tailored to a wide array of application needs based on area to be covered and the required density of measurements.

LiDAR for forest measurements

There is significant interest in LiDAR applications in forest assessment as evidenced by the number of recent publications and technical/scientific conference sessions devoted to the subject. Sixteen technical sessions were devoted to LiDAR studies at the American Society for Photogrammetry and Remote Sensing 2004 annual meeting (ASPRS 2004). A number of recent conferences have been devoted exclusively to LiDAR use in forestry applications (Wulder *et al.* 2002, Canadian Remote Sensing Society 2003, Hyyppä *et al.* 2003; Natscan[6], US Forest Service[7], SilviScan[8]).

With expectations ever increasing for development of more rapid and reliable forest measurements, it is no wonder that interest in LiDAR has grown at a rapid pace over the past few years. Field determination of individual tree heights is a time-consuming process that generates information that can have considerable variability based on instruments used and the individual capabilities of field personnel. Data from commercial LiDAR systems have been demonstrated to be useful for determination of individual tree heights (Eggleston 2001, Persson *et al.* 2002, Brandtberg *et al.* 2003, McCombs *et al.* 2003, Popescu and Wynne 2004) and average stand heights (Næsset 1997a, Young 2000, Young *et al.* 2000, Andersen *et al.* 2005).

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[5] Mention of company or product names is for information only and does not constitute official endorsement by Mississippi State University or the authors.

[6] Laser-scanners for Forest and Landscape Assessment – Instruments, Processing Methods and Applications. Institute for Forest Growth and Department of Remote Sensing and Land Information Systems, Faculty of Forest and Environmental Sciences – Albert-Ludwigs-University, Freiburg. 3–6 October 2004. Freiburg, Germany.

[7] US Forest Service LIDAR Concepts and Resource Applications Workshop. 17–19 May 2005, Salt Lake City, Utah.

[8] SilviScan: Lidar Applications in Forest Assessment and Inventory. Department of Forestry, Virginia Polytechnic Institute and State University, US National Aeronautics and Space Administration. 29 September – 1 October 2005. Blacksburg, Virginia, USA.

Two other important pieces of information for forest management are stand density and canopy cover (crown closure). Tree and stand height information, in conjunction with stand density (Young 2000, Young *et al.* 2000, McCombs *et al.* 2003) or canopy cover (Næsset 1997b) derived from LiDAR, is useful in developing timber volume estimates (Næsset 1997b, Means *et al.* 2000, Parker and Evans 2004). Tree heights are determined from accurate measurements with LiDAR of both the elevation of the ground surface and that of the canopy surface. The difference between these two measurements gives the height of the stand or in some studies (e.g., McCombs *et al.* 2003) the height of individual trees. Stem density derived from individual tree recognition (McCombs *et al.* 2003, Popescu *et al.* 2003) coupled with tree height (which in some timber types has a strong relationship to stem diameter) provides the way by which timber volumes can be estimated over large areas with LiDAR (Parker and Evans 2004). When examined over time, LiDAR measurements also have the added benefit of providing information relative to detection of changes in forest areas due to both tree removal and growth (Yu *et al.* 2004).

The following project summaries illustrate specific examples of how LiDAR data can be used to derive much of the important measurement information alluded to previously. These projects represent both completed and ongoing research related to LiDAR use at different scales of forest assessment. They cover a range of forest types and associated geographic variability, and have used a common analytical framework and similar data handling procedures. Thus, the adaptability of LiDAR to providing useful measurement information for forest assessment is further supported in addition to what has already been described above.

Individual Tree Measurements

Location and height

Individual tree height measurement has long been recognized as an important starting point for forest assessments. Several LiDAR-based projects have used this assertion for forest analysis (e.g., Hyyppä *et al.* 2001, Persson *et al.* 2002, Brandtberg *et al.* 2003, Popescu and Wynne 2004). Research at MSU has also focused largely on aggregation of individual tree characteristics for timber volume estimation and determination of other stand parameters of interest.

The first problem in single-tree measurement concerns determination of tree locations. The general approaches used to date at MSU have drawn primarily from work described by McCombs *et al.* (2003). They generated a high-resolution canopy surface model (grid) by use of linear interpolation from a triangular irregular network (TIN) of LiDAR first returns. This grid was then examined by means of a search algorithm that finds local high points in the surface that are assumed to be tree tops. Heights of individual trees recognized using the LiDAR data were derived by differencing the elevation values of the canopy surface and ground elevation models at the location of each identified stem. McCombs *et al.* (2003) indicated that, using these procedures, tree recognition accuracies of over 80% could be achieved in tree spacings typical of those found in pine plantations of the southern US, particularly if LiDAR is used in conjunction with multispectral data. Trees that were not recognized were, on average, over 1 m shorter than those accurately identified by their methods.

These methods of tree identification and height determination have generally been adopted for other applications including: forest inventory (Mitchell 2004, Parker and Evans 2004), forest structure characterization (Zimble *et al.* 2003), and forest visualization (Fujisaki *et al.* 2003, Fujisaki 2005). Tree identification is also an important starting point in analysis of other parameters such as crown width, crown length, and leaf area.

Crown dimensions

Determination of crown dimensions, particularly with respect to leaf area assessment, has proven to be challenging. Harrington (2001) reported a strong relationship ($R^2 = 0.84$) between field- and LiDAR-estimated tree heights in unthinned loblolly pine (*Pinus taeda* L.) research stands; however, relationships for average crown diameter (ACD) and height to the center of leaf area (CLA; assumed as the height to the middle of the crown), while significant, were somewhat weak with R^2 values of 0.55 and 0.40, respectively. Other studies have also found that the relationships between field- and LiDAR-derived crown dimensions, although significant, were not exceptionally strong. Næsset and Økland (2002) utilized a number of derived percentiles of LiDAR pulse distributions to predict individual tree crown length and height to the crown base and obtained R^2 values of 0.51 to 0.53 for these variables, respectively. Popescu *et al.* (2003) obtained R^2 values of 0.62-0.63 for models to estimate pine and hardwood crown diameter.

Using data from destructively sampled trees, Roberts *et al.* (2003) found a strong relationship ($R^2 = 0.81$) between individual tree leaf area (LA) and diameter at breast height (DBH). Crown volume in combination with tree height provided an even stronger relationship with LA ($R^2 = 0.83$). Crown volume is derived from parameters that might be measurable with LiDAR; thus, the authors suggest that it might be possible to estimate LA, and therefore determine stand leaf area index, based on this relatively new remote sensing tool. This goal, however, has yet to be fully realized (Roberts *et al.* 2005). Here, tree identification and height measurements, as reported elsewhere (Young *et al.* 2000, Næsset and Økland 2002, McCombs *et al.* 2003, Popescu and Wynne 2004), were within expected deviations from actual values for four- and 16-year-old planted pine stands. They reported net identification accuracy of 87.6 to 89% overall for tree identification across all sites and height estimates were within 1m of field observations. Determination of leaf area was, however, more problematic, due to the difficulty in determination of crown dimensions from LiDAR data, in particular, crown diameter, height to crown base and height to crown center. Harrington (2001) also encountered these problems. Popescu *et al.* (2003) reported slightly better results through regression of field- to LiDAR-derived pine and deciduous crown diameters of dominant trees ($R^2 = 0.62$ to 0.63) where height estimates were included in the prediction models.

An unstated truth related to these problems is that field measurement of crown parameters also has significant potential for imprecision that could contribute to weak correlations to LiDAR-derived values (Roberts *et al.* 2005). Rapid improvements in LiDAR technology, coupled with refined analytical techniques for better tree assessments will undoubtedly result in more positive outcomes to these complex measurement tasks.

Forest Inventory

A logical goal of LiDAR as a measurement tool is incorporation of this technology into operational forest inventories. Numerous authors have presented findings that demonstrate LiDAR's ability to measure trees and stands (Næsset 1997a, b; Magnussen *et al.* 1999; Means *et al.* 2000; Renslow *et a.* 2000; Hyyppä *et al.* 2001; Næsset and Bjerknes 2001; McCombs *et al.* 2003; Popescu *et al.* 2003, 2004). Most of these authors have indicated that their studies illustrate the potential utility of LiDAR in inventory applications and they further expressed a need for applications-oriented research to demonstrate the potential for operational use of LiDAR in these endeavours. There has been considerable effort in conducting the applications research to address this recommendation.

One approach taken to incorporate LiDAR into forest inventory is drawn from classic double-sampling theory. This type of sampling, described by Avery and Burkhart (2002), has been used in forestry for decades, typically with aerial photographs. Photogrammetrically estimated forest volumes (the large, Phase 1 sample) are associated with volumes based on limited field sampling (Phase 2). Double-sampling approaches allow credible estimates of forest volume to be achieved with smaller numbers of field plots than would normally be required in a traditional field-only inventory to meet a specific sampling error requirement.

A double-sample procedure using LiDAR is described by Parker and Evans (2004). This study was conducted on a mixed conifer site in Central Idaho. LiDAR data were flown with a nominal posting spacing of 2 m. A series of 360 Phase 1 rectangular plots (0.08 ha) were established in the LiDAR data strips. Within these plots, tree locations and heights were determined based on procedures for individual tree assessment described by McCombs *et al.* (2003). Measurements taken on 60 field plots (Phase 2) included tree diameters and heights. The relationship between diameter and height from the field sample was used to estimate tree volumes from the LiDAR-identified trees in the volume estimation procedure. The authors report a sampling error for the study of ±11.5% on the mean volume estimate in cubic feet, concluding that LiDAR provides the measurement precision to produce reliable results for forest inventory assessments, and that biases in the LiDAR measurements are adequately compensated through the double-sampling procedures.

Encouraging results obtained in the Idaho inventory tests provided impetus for two projects that further examined the operational feasibility of LiDAR-based double-sample inventory procedures in the southern U.S. A recently completed project examined a number of alternative estimation and data-processing procedures associated with LiDAR data collected on the Louisiana State University School Forest and adjacent industry lands. A second project involved an operational test of the double sample procedures to estimate timber volumes across approximately 26 000 ha of corporate timberland in Louisiana.

In the first Louisiana research project, investigations were undertaken to determine if differences in LiDAR posting density or data analysis techniques could influence volume estimation in pine- dominated timber stands. LiDAR data collected at 0.5 and 1.0 m post spacings were processed based on the procedures described by McCombs *et al.* (2003) and Parker and Evans (2004). Sampling errors ranged from 7.6 to 9.0% for scenarios that included or excluded use of regression-based adjustments to correct for height underestimation bias on individual trees identified in the LiDAR data prior to use of the LiDAR-derived measurements in the double-sample design. The height adjustment process increased sampling errors, but there were no significant differences between mean volume estimates derived from the 0.5 versus 1.0 m post spacing of LiDAR data. Parker and Glass (2004) suggest that, although there could be potential cost savings in using the lower density LiDAR data, caution should be used in extension of these procedures to immature conifer stands as the increased errors in individual tree detection could offset the gains achieved through lower LiDAR data collection costs.

The 0.5 and 1.0 m data were also used to generate LiDAR canopy surfaces that were either statistically smoothed or left in the original interpolated state (Parker and Mitchell 2005) prior to submission to the tree detection routines. The assumption was that higher-density LiDAR data would produce more variable canopy surfaces that would result in more false-positive tree locations and, therefore, generate problems in volume estimation under the former procedures. Again, as in the previously reported work (Parker and Glass 2004), Parker and Mitchell (2005) found low sampling errors (7.65 to 9.52% for mean volume estimates) and no statistical differences between volume estimates based on trees detected in either smoothed or unsmoothed canopy surfaces.

Results from the industrial operational test with LiDAR data averaging 1.9 returns per m^2 indicate that sampling precision was improved when data were analyzed by age class strata for ages 6 to 28 years in loblolly pine (*Pinus taeda*) stands. Volume estimates were significantly improved in the age class strata by adjusting for height estimation bias in the LiDAR and predicting tree dbh using adjusted heights with nonlinear equations containing age as an independent variable. For strata containing a majority of merchantable trees, within strata sampling errors for volume were less than 10% and the overall sampling error was less than 3% when using approximately 50 ground plots (0.05 acres) per stratum and an 8:1 ratio of LiDAR:ground plots. Degrading the ground sample to 15 plots in each merchantable stratum resulted in within-stratum sampling errors of approximately 15% and an overall error of 5% across all strata.

The volume estimation procedures described by Parker and Evans (2004), Parker and Glass (2004), and Parker and Mitchell (2005) all point to the need for field plots for local adjustment of tree height-diameter relationships in order to produce reliable volume information from LiDAR data. Yet these and the other findings given above, still point to the need for site-dependent relationships to be established for volume estimation. This dependency might someday be overcome by use of alternative procedures that are being investigated and are summarized below.

Roberts *et al.* (2003) suggested that if tree crown dimensions could be adequately measured through use of LiDAR, better estimates of leaf area might be obtained, which could be valuable for other uses such as volume estimation. If crown dimension measurements can be used to estimate leaf area and height to the center of leaf area, then this information could be used to predict stem diameter (Dean *et al.* 2002). The height to the center of leaf area can be assumed to occur at the widest point of the crown (Morgan and Cannell 1994). Given that crown diameter might be determined, and total height is easily obtained, it may be possible to further automate volume estimation with LiDAR data at the individual tree level using principles of the uniform stress hypothesis (Dean *et al.* 2002). The advantage here is that tree dimensions related to volume would be determined automatically with remote sensing, thus reducing or eliminating dependence on extensive field sampling. This could also lead to volume estimation procedures independent of site-specific regression models that currently cannot be used across different regions. The difficulties, as stated by Harrington (2001) and Roberts *et al.* (2005), primarily involve accurate measurement of crown dimensions. A new approach, in collaboration with scientists at Louisiana State University, is examining the fit of a probability density function to the LiDAR canopy point distribution to provide a reliable estimate of height to the center of leaf area at the plot level. Using stem diameters estimated from the uniform stress hypothesis (Dean *et al.* 2002) and based on the crown parameters obtained from the probability density function, Mitchell (2004) suggested that volume estimates might be possible without the need to calibrate specific height-diameter models.

Forest Structure and Type Assessments

As already documented, much LiDAR research has addressed basic forest measurements. Yet a number of characteristics of LiDAR data may also allow generation of additional information suitable for stand- and landscape-level management. Information on the horizontal and vertical structure of both the overstory and understory is needed for a wide variety of applications. Some of the previously discussed applications (e.g., McCombs *et al.* 2003) readily illustrate the ability to determine horizontal distributions of stems (tree locations) and vertical (height) characteristics of the forest canopy. Species (or species group) composition information at the stand level is also needed for planning a number of forest management operations. The studies discussed below illustrate some of the ways that forest structure and composition are being evaluated with LiDAR and work is also continuing in these areas at the present time.

Stand structure assessment

Horizontal and vertical distribution of forest components have been assessed in a number of studies through analysis of individual structural measures such as tree or canopy height, canopy profiles, stem density, and basal area (Lefsky *et al.* 1999; Means *et al.* 1999, 2000; Renslow *et al.* 2000; Harding *et al.* 2001; Hyyppä *et al.* 2001; Næsset and Bjerknes 2001). Yet, until recently, such information has not been compiled into meaningful data layers for use in landscape-level models for applications such as wildlife habitat suitability analysis. Zimble *at al.* (2003) demonstrated that it is possible to assess forest structure at the landscape scale. At a study site in central Idaho, they used procedures based on those described by McCombs *et al.* (2003) to locate and measure tree heights. The tree locations and heights were used to generate a grid-based model of tree height variance. Differences in height variance within grid cells were used to define simple structural classes that were represented in a final grid model of the study area. Although based on a limited sample, high classification accuracy (97%) indicated a reasonable assumption that the methodology could be suitable for landscape-level vertical structure mapping in the Rocky Mountain west. In similar but much more detailed fashion to that illustrated in Zimble *et al.* (2003), Andersen *et al.* (2005) illustrated how a number of structural variables of interest could be composited from LiDAR through grid-based modeling.

Forest type prediction with LiDAR

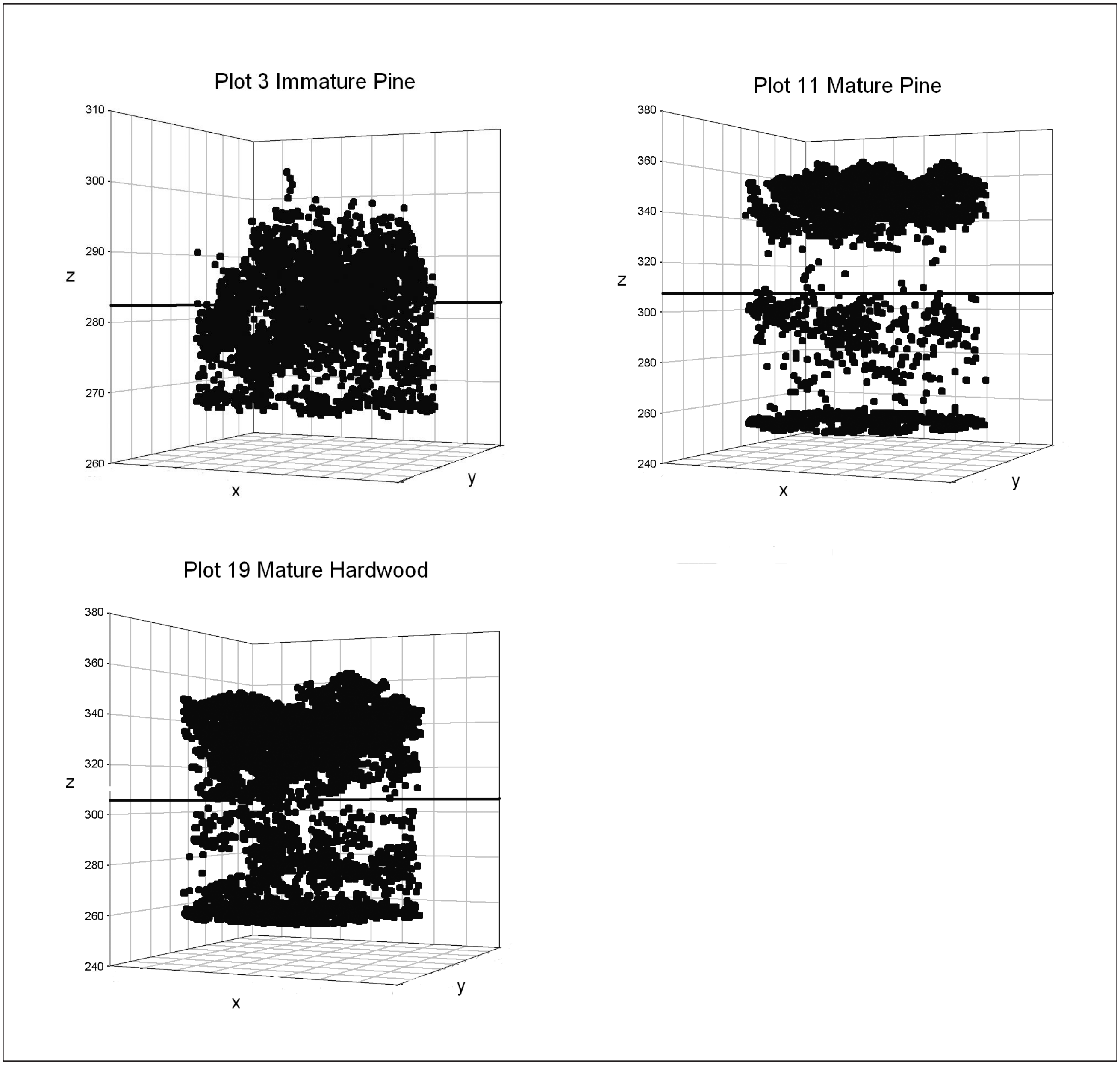
Recent research using LiDAR to determine forest canopy structure indicates the possibility for classifying different forest conditions. Return energy profiles (signal intensity plotted as x, and height as y) produced by the SLICER (Scanning LiDAR Imager of Canopies by Echo Recovery; Harding *et al.* 2001) have been used to evaluate ecologically significant differences in canopy structure. Persson *et al.* (2003) utilized extremely high-density (15 points per m^2) LiDAR point clouds to identify and classify individual trees. Such studies led to the question "Can LiDAR point clouds be used to classify different forest types?" Initial inspection of LiDAR returns from three different stands provided some indications that conditions could be classified (Fig. 1). Differences in canopy structure and assumed difference in reflectivity of the laser (LiDARs generally use near-infrared lasers; conifers and broadleaf trees generally have different reflectivity in the near-infrared spectrum) appeared to make it possible to distinguish between general forest types.

Douglas *et al.* (2003) derived two variables, mean point density and mean return intensity, from LiDAR canopy hits. Using discriminate analysis, they attempted to classify the LiDAR returns for 44 plots as immature pine, mature pine, or mature hardwood for stands in east-central Mississippi. The overall proportion of correctly classified plots was 93.2%. Using the same procedures to classify plots on a southeast Louisiana site, Douglas (2004) achieved a 77.8% classification accuracy for the same categories. Differences in accuracy were attributed to the development stages of the two pine classes. The immature pine stands at the Louisiana site were structurally more similar to the mature pine stands than was observed at the Mississippi site. This contributed to classification confusion between the pine classes in the Louisiana plots.

Combining the pine plots at the Louisiana site into a single class after the initial discriminant analysis resulted in a 97.8% correct classification of pine versus hardwood. These findings, while not definitive due to limitations in sample size and range of representative conditions, illustrate the potential to extract meaningful forest classification information from LiDAR point clouds.

Summary

The level of interest in use of LiDAR for forest assessments has risen at a near exponential rate over the past decade. With the introduction of waveform LiDAR and high-resolution scanning systems in the early 1990s, many researchers immediately saw the potential of this new tool for forestry applica-


Plot 3 Immature Pine

Plot 11 Mature Pine

Plot 19 Mature Hardwood

Fig. 1. 3-D scatterplots of all LiDAR returns from immature pine, mature pine, and mature hardwood plots from the MSU John Starr Memorial Forest, Winston County, MS. Measurement units are in feet (from Douglas 2004).

tions. National and international meetings have devoted a significant number of technical sessions to this technology, and recently a number of major meetings have been devoted exclusively to LiDAR use in forest assessments.

Projects are now transitioning from purely research investigations to more operational tests of this technology. This is evidenced by the migration of studies from single-tree and plot summary assessments into full-scale inventory protocols. For example, one study has demonstrated an operational test of the double-sample inventory protocol for a large area of corporate timberland in the southern U.S. We suspect that other such tests have been conducted or are being planned elsewhere in other regions of the world. The positive results illustrated here that cover a broad spectrum of conditions support strongly the contention that LiDAR is indeed a candidate as the next major resource measurement tool for forest management.

Even with the large body of research into use of LiDAR in forestry, interactions between LiDAR pulses and forest canopies are in many ways still not well understood. Several basic measurement issues need to be addressed. These include development of more robust procedures for estimating tree and stand parameters, assessment of sampling issues that address post spacing and footprint size with respect to tree detection (Evans *et al.* 2001), and examination of the relationship of return intensity to tree characteristics. There are also a number of fundamental questions with regard to how well LiDAR data can be used to measure understory vegetation parameters.

Through these research projects, more robust approaches to LiDAR analysis are being sought in order to provide for consistent measurements of tree and forest variables in an automated fashion over a wide range of stand conditions:

1) Tree identification in spatially periodic populations (e.g., pine plantations) as a function of theoretical LiDAR point density.
2) Assessment of understory density from LiDAR returns (utility in wildlife habitat assessment and fire fuels models).
3) Individual-tree growth and yield modeling from time-series LiDAR data on pine plantations.
4) Analysis of optimal sampling intensity in double-sample inventory protocols based on LiDAR data.
5) Utilization of LiDAR data and derived individual-tree measurements in immersive visualization environments for stand assessment.

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