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LiDAR remote sensing of forest structure

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Abstract: Light detection and ranging (LiDAR) technology provides horizontal and vertical information at high spatial resolutions and vertical accuracies. Forest attributes such as canopy height can be directly retrieved from LiDAR data. Direct retrieval of canopy height provides opportunities to model above-ground biomass and canopy volume. Access to the vertical nature of forest ecosystems also offers new opportunities for enhanced forest monitoring, management and planning.

Key words: biomass, forest structure, laser altimetry, LiDAR, remote sensing.

I Introduction

Laser altimetry or Light Detection And Ranging (LiDAR) is an active remote sensing technology that determines ranges (i.e., distances) by taking the product of the speed of light and the time required for an emitted laser to travel to a target object. The elapsed time from when a laser is emitted from a sensor and intercepts an object can be measured using either (i) pulsed ranging, where the travel time of a laser pulse from a sensor to a target object is recorded; or (ii) continuous wave (CW) ranging, where the phase change in a transmitted sinusoidal signal produced by a continuously emitting

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laser is converted into travel time (Wehr and Lohr, 1999). At present, the majority of LiDAR systems in use are based on the pulse ranging principle and, according to Wehr and Lohr (1999), only one commercial CW airborne laser scanner exists. Consequently, CW lasers have not been used in LiDAR applications for forestry and it should be noted that all subsequent references to LiDAR systems implicitly refer to pulse ranging laser systems.

Applications of LiDAR systems have developed recently through parallel advances in global positioning systems (GPS) and inertial navigation systems (INS), also referred to as inertial measurement units (IMU). Applications of LiDAR include flood risk mapping (McArdle *et al.*, 1999); bird population modelling (Davenport *et al.*, 2000); ice sheet mapping (Krabill *et al.*, 1995); pesticide application (Walklate *et al.*, 1997); econometric modelling (Cowen *et al.*, 2000); terrain modelling (Flood and Gutelius, 1997; Kraus and Pfeiffer, 1998); and land cover classification (Schreier *et al.*, 1985), as well as an array of atmospheric (Matrosov *et al.*, 1998) and extra-terrestrial (Kreslavsky and Head, 1999; Neumann, 2001) applications. For the details of LiDAR theory, the reader is referred to Baltsavias (1999a) and Wehr and Lohr (1999).

Various remote sensing systems and techniques have been explored for forestry applications and are reviewed by Weishampel *et al.* (1996), Wulder (1998), and Lefsky *et al.* (2001a) with a comparison of various remotely sensed data sources with LiDAR. Typically, most optical sensors are only capable of providing detailed information on the horizontal distribution and not the vertical distribution of vegetation in forests. LiDAR remote sensing is capable of providing both horizontal and vertical information with the horizontal and vertical sampling dependent on the type of LiDAR system used and its configuration (i.e., discrete return or full waveform LiDAR).

In the early 1980s, the Canadian Forestry Service demonstrated the applicability of profiling LiDAR for the estimation of stand heights, crown cover density and ground elevation below the forest canopy (Aldred and Bonner, 1985). In the same period, LiDAR was utilized to map tropical forests in Central America (Arp *et al.*, 1982). MacLean and Krabill (1986) also noted that the application of LiDAR for estimating forest attributes and terrain mapping may be possible as the amplitude waveforms of the reflected laser energy from a forest canopy exhibited similar characteristics to waveforms recorded from mapping bathymetry. Krabill *et al.* (1980) showed that contouring data from LiDAR data and from photogrammetry techniques agreed within 12–27 cm in open areas and 50 cm in forested areas. For a comparison of LiDAR to photogrammetry, the reader is referred to Baltsavias (1999c). Given the ability to accurately measure topography, it was realized that certain forest attributes could be quantified from forest canopy profiles derived from LiDAR data. Specifically, various forest attributes can be directly retrieved from LiDAR data, such as canopy height, sub-canopy topography, and vertical distributions of canopies. Attributes that can be predicted using empirical models from LiDAR data, include above-ground biomass, basal area, mean stem diameter, vertical foliar profiles and canopy volume (Means *et al.*, 1999; Lefsky *et al.*, 1999a, b; Dubayah and Drake, 2000).

The goal of this paper is to provide a review of LiDAR applications for the remote sensing of forests. Introductory sections provide background on the use of LiDAR for remote sensing of forests and information on how the main LiDAR systems used for forestry applications operate and how they differ from one another (i.e., the intent is not to review all LiDAR sensors, but rather those commonly cited in the literature). This review summarizes the literature specific to: (i) the characterization of canopy density, closure and height; and (ii) the estimation of biomass and gross-merchantable volume. The paper concludes with some insights on LiDAR for forest monitoring, including a preview of foreseen applications and comments on what further research is required.

II An overview of LiDAR systems

LiDAR systems are based on the principle of laser ranging. Young (1986) describes that with the laser process, a highly directional optical light can be created, thus yielding the high collimation and high optical power required for ranging. Lasers were demonstrated to be advantageous for this type of measurement as high-energy pulses can be realized in short intervals and short wavelength light can be highly collimated using small apertures. The laser, coupled with a receiver and a scanning system, enables the distribution and sensing of points over a swath defined by the instrument scan angle and flying height of the aircraft (Figure 1), whereas the distribution of points using earlier profiling systems were constrained to the along-track path of the aircraft.

1 Components of a LiDAR system

There can be significant variation in design across airborne LiDAR sensors, but the basic system components are fairly standard. An onboard commercial GPS receiver

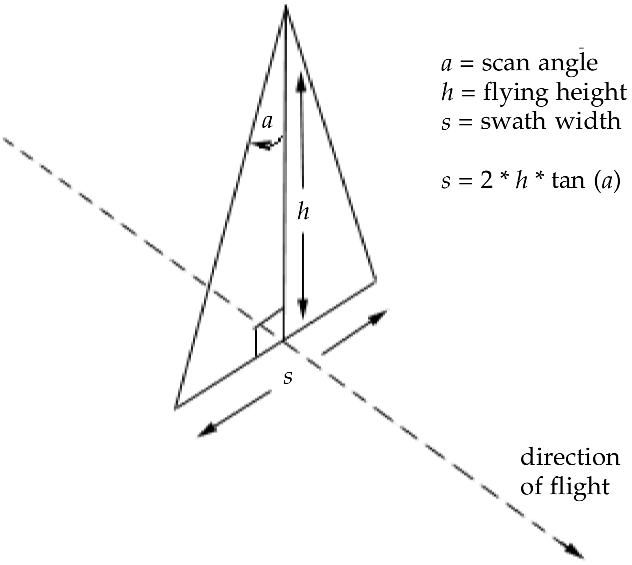

Figure 1 Swath width as a function of instrument scan angle and aircraft flying height

operating in conjunction with one or more ground stations as part of a differential GPS solution provides the position of the sensor. The orientation of the sensor is measured by an onboard IMU.

The laser subsystem is generally based on a solid-state, diode-pumped laser from a commercial laser manufacturer. The opto-mechanical structure of the transceiver is usually built around standard off-the-shelf optics and a custom mechanical support structure. Some sensors use custom optics designed specifically to optimize aspects of that particular sensor's performance. The receiver and signal processing electronics are generally designed from available commercial components augmented by custom electronic designs where necessary. In the receiver, optical/infrared detectors, predominantly avalanche photodiodes, available from a variety of manufacturers, are used. An off-the-shelf or custom time interval meter (TIM), essentially a precision clock, is used in each channel of the receiver (i.e., TIM unit for each return pulse recorded) or the full return waveform is captured using a digitizing board. Additional electronics in the receiver are implemented to record return intensity in systems that do not record the full waveform or to monitor additional information such as return pulse polarization.

Onboard storage of the data is generally to hard disk although many earlier systems, such as Optech's ALTM sensors, still use 8 mm tape. An onboard acquisition and control computer is generally housed in a separate rack from the sensor and provides the system set-up, monitoring and data recording functions along with access to the GPS, IMU and laser control functions. These control computers are predominantly built up from available commercial hardware on a VME or Ethernet backbone, running custom firmware specific to the sensor. A handheld operator interface or remote control unit such as a touch screen laptop completes the onboard hardware.

Post-processing of the LiDAR data is conducted on standard computer workstations using a combination of proprietary code for extracting and geo-coding the laser data and proprietary or third-party software for classifying and analysing the data. The only major requirement here is that because of the massive size of the LiDAR data point clouds, mapping workstations with a minimum of 1 GB RAM, and preferably 2 GB, are the norm.

2 Types of LiDAR systems

LiDAR systems used in forestry applications can be categorized as either 'discrete return' systems or 'full waveform' systems and differ from one another with respect to how they vertically and horizontally sample a canopy's three-dimensional structure (Figure 2). The vertical sampling of LiDAR systems relates to the number of range samples recorded for each emitted laser pulse. The horizontal sampling is determined by the area of the footprint and the number of such footprints, or 'hits', per unit area.

Discrete return systems typically allow for one (e.g., first *or* last), two (e.g., first *and* last), or a few (e.g., five) returns to be recorded for each pulse during flight. Conversely, a full waveform LiDAR system senses and records the amount of energy returned to the sensor for a series of equal time intervals. The number of recording intervals determines the amount of detail that is present in a laser footprint. An amplitude-against-time waveform is constructed from each time interval and is representative of the area of

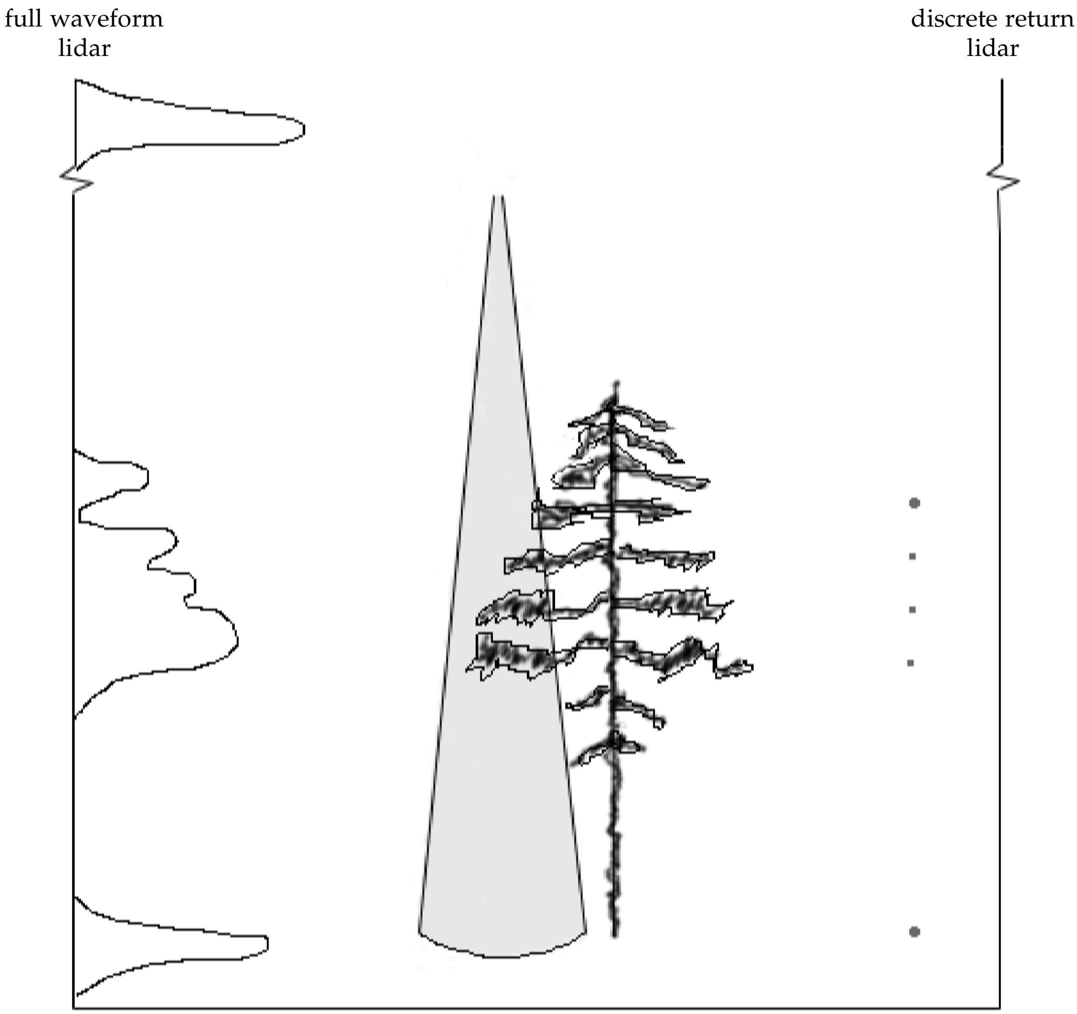

Figure 2 Differences between discrete return and full waveform vertical sampling

interception. For forested environments, the result is a waveform indicative of the forest structure (i.e., from the top of the canopy, through the crown volume and understory layer, and finally to the ground surface).

The information content of the returned laser signal is also a function of the horizontal sampling area. The sensor configuration of the beam divergence results in a circular sampling area (i.e., footprint), which increases in size with distance from the sensor (i.e., altitude). The footprint for most discrete return systems is on the order of 0.2 to 0.9 m. For the full waveform systems, the footprint size may vary from 8 m to 70 m (Means, 1999; Harding *et al.*, 2000). As a result, large footprint, full waveform LiDAR will contain information on the forest canopy and multiple forest elements rather than individual trees, whereas small-footprint discrete return LiDAR, will only sense a portion of forest elements (e.g., the side of a tree crown versus the top or peak of the crown).

For full waveform LiDAR, energy that is reflected back above a specific noise threshold is recorded for given time intervals. The sensitivity of the sensor is at the level of a few photons per interval and, as a result, even small volumes of vegetation can influence the shape of the return waveform. The waveform data can be translated into a detailed description of vertical canopy volume distribution (Lefsky *et al.*, 1999b) and can be used to model light transmittance in forest canopies (Parker *et al.*, 2001). With discrete return systems, the full vertical distribution of vegetation is not sensed. Instead, only a portion of the canopy and the ground level is recorded. The ability to obtain sub-canopy information depends on the ability of the laser to penetrate the canopy given its canopy structure. Discrete return systems are capable of recording the amplitude (i.e., intensity returns) of each detected return; however, more research is required in order to assess the information content of the intensity return data. Despite the inability of discrete return systems to digitize full waveforms, both types of LiDAR systems are equally capable of deriving canopy height, which has been demonstrated as a strong predictor of other forest structural parameters (Lefsky *et al.*, 2001b). Means (1999) provides a detailed comparison of discrete return and full waveform LiDAR remote sensing systems.

For forestry applications, the ability of small footprint, discrete return sensors to capture multiple returns – to penetrate beyond the first reflective surface of the canopy – is a critical characteristic. Most commercial LiDAR systems capture between two and five returns; referred to as multipulse or multiecho capability. Very few field projects have reported detailed statistics or analysis based on the number of returns seen in each band or examined the variance of this parameter against canopy type or operational variables. Sample data sets suggest that very few fifth echoes (i.e., <0.1%), are captured even in the densest vertical canopy, while less than 1% of pulses return a fourth echo (Ron Roth, LH Systems, personal communication, 1999). This is an area that requires further study and clarification, but it suggests that capturing three echoes per pulse may be the optimal experimental design, especially if last pulse logic is employed by the sensor. When considering last pulse logic it is important to recognize the distinction between capturing two or more returns sequentially and capturing the first/last returns detected. For example, given a hypothetical situation where there are seven detectable returns from seven unique surfaces (canopy, sub-canopy, litter, ground, etc.), a two-echo system will return elevation values from surfaces one and two, a five-echo system from surfaces one, two, three, four, and five and a first/last system from surfaces one and seven. This first/last pulse data capture is accomplished by implementing last pulse logic in the receiver electronics to sample and hold all returns after the first but only record the final return. For research where capturing the true vertical profile of the canopy is a critical measure, it is best to consider using full waveform capture as opposed to discrete return measurements.

3 Airborne LiDAR systems for forest studies

Dubayah and Drake (2000) state that three characteristics can be used to classify LiDAR systems for forestry. These include: (i) the manner in which the return signal is recorded (i.e., range is measured based on discrete returns or full waveforms); (ii) footprint size (i.e., small (a few centimeters) or large (tens of meters)); and (iii) sampling rate and scanning pattern. Early LiDAR systems recorded returns along a single flight path or profile, generally using small footprints of 1 m in diameter or smaller (Nelson *et al.*, 1984, 1988a; Aldred and Bonner, 1985; Ritchie *et al.*, 1993). The Airborne Oceanographic Laser (AOL) (Hickman and Hogg, 1969) was among the first LiDAR systems used for forestry applications, but was gradually replaced by custom prototype LiDAR systems developed specifically for terrestrial applications. These in turn have evolved into today's existing airborne LiDAR systems. For a more comprehensive listing of available LiDAR systems across the globe, see Baltsavias (1999b) or online resources at http://www.airbornelasermapping.com (last accessed 26 November 2002). Discrete return LiDAR data used in recent forest studies are predominantly acquired using Optech's Airborne Laser Terrain Mapper (ALTM) or custom built/modified airborne laser scanners, whereas full waveform LiDAR data are acquired using either the Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) or the Laser Vegetation Imaging Sensor (LVIS).

Discrete return LiDAR is becoming an operational tool in remote sensing. LiDAR sensors are aircraft-mounted laser rangefinders designed to measure the three-dimensional coordinates of a passive target. The basic principles and design constraints of LiDAR are well-known (Wehr and Lohr, 1999; Baltsavias, 1999a); however, there is still significant variation in design from instrument to instrument, especially across custom-designed sensors. The general characteristics and specifications of the current generation of commercial discrete return systems used for topographic mapping are summarized in Table 1.

Over the past decade there have been dramatic improvements in LiDAR technologies. These include: (i) increases in pulse repetition rates; (ii) greater storage capacities; (iii) improved positioning accuracy; and (iv) higher flying altitudes and hence, greater swath width. This has provided for large area sampling with aerial surveys. For example, the Optech ALTM series are small-footprint discrete return scanning LiDAR systems that record the first and last return of a particular laser pulse (Flood and Gutelius, 1997). The ALTM LiDAR systems utilize a laser with a wavelength of 1047 nm and laser pulse repetition rates of up to 33 kHz (Optech Inc.: http://www.optech.on.ca, last accessed 26 November 2002).

The SLICER was developed at the NASA Goddard Space Flight Centre as a scanning modification of a profiling laser altimeter (Blair *et al.*, 1994). The SLICER is a LiDAR system that digitizes the backscattered return signal resulting in the capture of a full waveform representing the vertical distribution of illuminated surfaces within the laser footprint (Harding *et al.*, 2000). The SLICER full waveform sensor is characterized by a laser wavelength of 1064 nm; a pulse frequency of 80 Hz; and five cross-track footprint sizes commonly ranging from 5 m to 15 m. Following the evolution of NASA LiDAR systems, Laser Vegetation Imaging Sensor (LVIS) (Blair *et al.*, 1999) evolved from SLICER and is the airborne simulator for the Vegetation Canopy Lidar (VCL) mission (Dubayah *et al.*, 1997). LVIS is a large footprint full waveform instrument capable of recording data across a 1 km swath with footprint sizes varying from 1 m to 80 m with a 25 m footprint typically utilized. The VCL is a planned spaceborne LiDAR intended to collect full waveform data to characterize the three-dimensional structure of the terrestrial surface of the Earth.

Table 1 Characteristics of typical commercial discrete return scanning systems

Specification	Typical value
Wavelength[a]	1.064 μm
Pulse repetition rate	5–15 kHz (50 kHz max)
Pulse energy	100s μJ
Pulse width	10 ns
Beam divergence	0.25–2 mrad
Scan angle (full angle)	40° (75° max)
Scan rate	25–40 Hz
Scan pattern	Zig-zag, parallel, elliptical, sinusoidal
GPS frequency	1–2
INS frequency	50 (200 max)
Operating altitude	500–1000 m (6000 m max)
Footprint	0.25–2 m (from 1000 m)
Multiple elevation capture	2–5
Post spacing	0.5–2 m
Accuracy (elevation)	15+ cm
Accuracy (planimetric)	10–100 cm
Post-processing software[b]	Proprietary
Price (standard)	US$850K–$1,000K
Price (custom)	US$1,000K–$2,000K
Delivery (standard)	20–26 weeks

Notes:

[a] Generally diode-pumped Nd:YAG, Nd:YLF and Nd:YVO_4 although there are some systems operating at 1.5 μm.

[b] Refers to geo-referencing of laser slant ranges to an established reference frame, normally WGS84.

III LiDAR remote sensing of forest structure

Much of the original motivation for investigating the application of LiDAR for measuring forest attributes can be traced back to early studies by Arp *et al.* (1982), Nelson *et al.* (1984) and MacLean and Krabill (1986). MacLean and Martin (1984) used cross-sectional photogrammetric and densitometric methods to demonstrate that the cross-sectional area of a forest canopy profile was linearly related to the natural log of timber volume. It was assumed that if LiDAR could be used to develop accurate canopy profiles, then estimates of gross-merchantable volume could be made.

In many respects, a research cycle can be observed in the literature. Whereas earlier studies have been limited primarily by technology, more recent studies have benefited from a suite of scanning and profiling laser altimeters capable of recording a discrete quantity of laser returns or the full waveform of a pulse. The focus of earlier studies was on establishing statistical relationships between laser-derived measurements with ground-based measurements in the form of predictive linear models (Nelson *et al.*, 1984). With significant advances in technology, the same needs exist to verify that new LiDAR systems are capable of matching previous results, if not improving upon them.

Furthermore, with the proposed Vegetation Canopy Lidar (VCL) project (Dubayah *et al.*, 1997), airborne simulators such as the LVIS are now being tested.

1 An overview of how canopy height is calculated from LiDAR data

A requirement for calculating canopy heights using both discrete return and full waveform LiDAR data is the ability to identify some ground reference level below the canopy. In the case of discrete return LiDAR data, canopy height estimates are calculated by taking the difference between those LiDAR returns not classified as ground and a surface representative of the terrain, which is typically interpolated from remaining returns after the point cloud has been filtered using a vegetation removal algorithm.

Terrain mapping surveys are typically carried out using a discrete return scanning LiDAR system. Full waveform LiDAR systems are primarily used by researchers for science applications and have yet to be truly commercialized. Creating an accurate representation of the ground surface consists of removing all nonground returns (e.g., vegetation and buildings) from the three-dimensional point cloud. Axelsson (1999) refers to this process as filtering. Different filtering techniques exist and are either based on statistical criteria (Kraus and Pfeiffer, 1998) and/or morphological criteria (Kilian *et al.*, 1996). An explicit assumption made in most classifiers applied to discrete return LiDAR data is that the lowest returns in the three-dimensional point cloud are ground returns. Care must be taken to pre-process LiDAR data to ensure that spurious returns (e.g., outliers and gross errors) caused by errors in the TIM unit, which is responsible for time-stamping returns, or from atmospheric effects, are removed prior to classification. These errors are easily identified as exaggerated depressions or spikes with improbable ranges in the three-dimensional point cloud. The assumption that the lowest returns are in fact ground may hold in urban, clear and open (e.g., deserts), and sparsely vegetated areas, but may not hold in forested or densely vegetative areas, where the possibility exists that the ground itself is completely or partially masked by low-level vegetation. Filtering and classification of the three-dimensional point cloud produced by discrete return scanning LiDAR systems is a challenge and is a focus of current research. Baltsavias (1999c) comments that interpreting the three-dimensional point cloud without ancillary optical imagery is indeed a challenge.

For full waveform LiDAR data, canopy heights can be calculated by converting the elapsed time difference between the peaks of the two most prominent modes in the amplitude waveform into range. According to Roberts (1998), the highest peak of the largest mode in a waveform does not necessarily always correspond to the highest point in the canopy, but is instead a function of the canopy structure (e.g., density and closure). Time differences can also be calculated between the leading and trailing edges of the two most prominent modes in the amplitude waveform as demonstrated by Nilsson (1996). Harding *et al.* (2001) present methods of developing representative canopy height profiles of the relative vertical distribution of canopy surface areas from full waveform SLICER data.

2 Canopy and tree height estimation

Many of the initial studies of the application of LiDAR for forestry focused on verifying through statistical analysis that LiDAR could be used to accurately measure forest attributes. The focus has been on canopy tree height given the nature of this attribute as a predictor variable for other forest attributes, such as biomass and volume (Arp *et al.*, 1982; Aldred and Bonner, 1985; Schreier *et al.*, 1985; MacLean and Krabill, 1986). However, it was suspected that the laser response to a forest canopy was not solely a function of tree height, but also a function of canopy closure and density, which could itself be studied by LiDAR (Nelson *et al.*, 1984; Aldred and Bonner, 1985). The significance of this hypothesis is that if canopy closure and density significantly influence laser response, then inaccurate canopy profiles may be derived from LiDAR data resulting in poor estimates of forest attributes. Nelson *et al.* (1984) surveyed an area exhibiting a gradient of canopy closures caused by gypsy moth damage using the AOL. They successfully verified the above hypothesis by showing how forest canopy profiles varied across the study area. Furthermore, Nelson (1997) demonstrates that spherical crown shapes in closed canopy situations lead to increased canopy height and a decrease in the variation in canopy height.

Ritchie *et al.* (1993) found that mean LiDAR heights from a first return LiDAR were significantly related to mean target heights in pine forest and grassland sites in Niger. Unlike Nelson *et al.* (1984), who explored the influence of known percentages of canopy closure on laser responses, Ritchie *et al.* (1993) used the coefficient of variation of mean tree height measurements from eight sites as an indicator of canopy closure. Large coefficients of variations were identified as an indicator of open canopies, whereas small coefficients of variations (e.g., less than 40%) were identified as an indicator of relatively closed canopies.

Nelson *et al.* (1988b), while studying a southern pine stand using AOL-derived LiDAR data, observed that the mean LiDAR height measurements from two distinct flight lines underestimated the ground measurements by approximately 30% or 4 m. Nilsson (1996) during his studies of a Scots pine stand using an airborne scanning laser mounted on a helicopter found that mean tree height was underestimated by 2.1–3.7 m. He had also investigated the effects of different beam divergences (i.e., 2.5, 5.0, 7.5 and 10.0 mrad) on LiDAR tree height measurements and concluded that differences in measurements were negligible and that all beam divergences were usable for measuring tree height. These beam divergences equate to footprint sizes ranging from 0.75 m to 3.0 m.

Næsset (1997) studied 36 stands covered by Norway spruce, Scots pine, or both using an Optech ALTM and also found that the mean of the LiDAR canopy heights within each stand underestimated ground-based estimates by 4.1–5.5 m. Although it was not explicitly stated, the influence of canopy structure on the laser response was considered by incorporating Lorey's height in the calculations for each plot. Lorey's height is a weighted mean of canopy height based on the basal area of individual trees to account for the influence of larger trees on the mean canopy height. Despite this change, the weighted mean of the LiDAR canopy height still underestimated ground-based estimates by 2.1–3.6 m. Finally, a 15 m × 15 m grid was draped over each stand and the largest tree from each grid cell was selected to derive a mean canopy height. This approach implicitly assumed that the laser response was related to the largest trees in the stand and resulted in mean differences between –0.4 m and 1.9 m. Regression of the LiDAR stand heights against ground reference stand heights accounted for 91% of the variation. Basal area and the number of trees per hectare, expressions of stand density, were determined to be significant parameters and when included in a multiple regression accounted for 94% of the variation.

The majority of LiDAR studies have focused on coniferous forests where tree crowns are conic in shape. Studies have shown that tree heights are underestimated by small-footprint LiDAR because of the low probability of a small-footprint laser pulse intercepting the apex of a conic crown (Nilsson, 1996; Næsset, 1997; Nelson *et al*., 1988b). Underestimates of tree heights given conic crown shapes should not be a deterrent for the use of small-footprint LiDAR, especially in the case of small-footprint discrete return LiDAR, since the differences between LiDAR canopy height and actual canopy height can be modelled (Magnussen and Boudewyn, 1998).

Of the 36 Douglas-fir plots studied by Magnussen and Boudewyn (1998), mean LiDAR canopy heights were shown to be 3.1 m lower than mean field heights. In their study, they outline why simple grid approaches, where only the maximum canopy heights within cells are retained for analysis (e.g., Næsset, 1997) provide the closest matches to target heights. Magnussen and Boudewyn (1998: 1017) state that 'the essence of the grid-based system is in the selection of a certain quantile of the LiDAR canopy height that best matches a known target height'. On the basis of this concept, they verify their hypothesis that 'the quantile of the LiDAR canopy heights matching in probability the fraction of leaf area above a desired height would be an unbiased estimator' (Magnussen and Boudewyn, 1998: 1030). Using these results, Magnussen *et al*. (1999) present two tree height recovery models. The assumption of one of the models is that 'observations are sampled with probability proportional to displayed crown area', while the second is 'derived from the probability that a laser beam penetrates to a given canopy depth' (Magnussen *et al*., 1999: 407). Both models were shown to eliminate the underestimation bias of mean LiDAR canopy heights.

The work by Magnussen and Boudewyn (1998) and Magnussen *et al*. (1999) is significant as it provides an explanation of laser response to forest canopy structure and how it can be dealt with to ensure accurate measurements of forest attributes derived from LiDAR data. Furthermore, evidence in support for Magnussen and Boudewyn's (1998) concept that a certain quantile of LiDAR canopy heights is a best estimate of actual ground height can be found in the work done by Ritchie *et al*. (1993) where the inclusion of the highest 10% of LiDAR measurements did not produce significant differences between LiDAR measurements and ground measurements, while significant differences were produced when the highest 15% of LiDAR measurements were used.

Beyond measuring mean tree heights for study plots and forest stands, some attention has been directed towards delineating individual tree crowns in LiDAR data and predicting individual tree heights. St-Onge *et al*. (2000) used small-footprint LiDAR data acquired from an ALTM to study individual trees. A Laplacian of Gaussian (LoG), a combined spatial filter and edge detection operator, was applied to a canopy height model to delineate individual tree crowns. The LoG requires the input of a spread parameter (σ), equivalent to the standard deviation of a distribution. This parameter is typically selected in an *ad hoc* fashion and the results are visually compared with the original images. The heights of 36 delineated trees in a canopy height model, corresponding to the highest LiDAR hit in the delineated crowns, were compared with corresponding ground measurements using a linear model ($r^2 = 0.90$, significant at 0.01).

With the recent work by Magnussen and Boudewyn (1998) and Magnussen *et al.* (1999), evidence clearly suggests that tree height can be recovered from LiDAR data just as accurately as from ground measurements, if not more accurately. St-Onge *et al.* (2000) demonstrate that the focus of the application of LiDAR may be shifting from the landscape/stand scale (e.g., forest inventories) to a local/tree scale (e.g., forest inventories stratified by species). The potential of LiDAR for forestry is slowly coming to fruition and as a result others have begun to explore LiDAR as an operational forestry tool (e.g., Tickle *et al.*, 1998, 2001).

SLICER-derived LiDAR measurements (e.g., mean canopy height, canopy reflection sum, quadratic mean height, canopy closure, ground reflection sum and median canopy height) of Douglas-fir plots have been combined to estimate various forest attributes (Means *et al.*, 1999). The coefficients of determination were found to be high for tree height (0.95), basal area (0.96), total biomass (0.96), foliage biomass (0.84) and canopy cover (0.94). The authors comment that these strong relationships are not surprising given the well established relationship between tree height and other forest attributes. An interesting note is that the SLICER data overestimated tree height. Means *et al.* (1999) attribute this overestimation to methodological differences in terms of how mean canopy height was calculated for the LiDAR and ground data.

3 Biomass and volume

MacLean and Krabill (1986) demonstrated that a LiDAR-generated canopy profile area was a significant variable in estimating gross merchantable timber volume. Multiple regression relating the natural log of timber volume to the full profile area and a profile area with a 10 m exclusion level produced promising results ($R^2 = 0.721$ significant at 0.01). By considering the profile area with a 10 m exclusion level and the predominant species of each plot expressed as a ratio of the volume of the predominant species to total volume, an R^2 value approaching 0.90 was obtained. Furthermore, they demonstrated that an overall R^2 value of 0.921 could be achieved if the LiDAR data were stratified by species. However, Nelson *et al.* (1988a) showed that stratification of southern conifers only slightly improved the accuracy of their volume and biomass estimates (1.0% and 0.4%, respectively).

Using 113 sample plots, Nelson *et al.* (1988a) tested two logarithmic equations for estimating biomass and volume with six LiDAR-derived canopy measurements to determine which model could best describe the variation in the ground measurements. The LiDAR height variables considered included average LiDAR canopy height of the three largest trees; mean plot height; mean canopy height; and modified canopy profiles with a 2 m, 5 m and 10 m exclusion level. From the 12 models tested, models applying the mean plot height metric derived from all LiDAR pulses as an input parameter were identified as the best models.

General linear models using one input parameter such as mean LiDAR plot height to estimate biomass and volume is not a standardized practice or the only way of making these estimates. Nilsson (1996) estimated stand volume as a function of: (i) the waveform area for a single laser return; (ii) the LiDAR height of a single laser return;

and (iii) the total number of LiDAR returns in a single plot. The regression equation model using these independent variables produced a coefficient of variation of 0.78 for estimates of stand volume.

As with any scientific model, results produced must be repeatable in order to gain widespread acceptance. Using the best biomass and volume equations identified in Nelson *et al*. (1988a), Nelson *et al*. (1988b) explored the ability of LiDAR to consistently repeat biomass and volume estimates over Appalachian hardwood forests predominantly composed of oak and hickory. They demonstrated that the difference between mean estimates of biomass and volume for distinct flight segments along the same flight line varied between 3% and 6%. A comparison of mean estimates of biomass and volume from two flight lines to actual ground measurements showed differences between 7% and 8%. The authors concluded that LiDAR measurements could be repeated and that with better registration of the laser track on the ground, the ability to model forest biomass and volume can only improve.

Wulder *et al*. (2000) have also shown the stability of LiDAR height estimates on a point and polygon basis. First, SLICER data generated the same heights for points collected from differing, yet overlapping flight lines. Secondly, estimates of the average tree height within forest inventory polygons from LiDAR data collected from differing flight lines were also found to be similar. A recent study by Lefsky *et al*. (1999b) reported on attempts to predict stem diameter of trees using LiDAR data, which is a required input for many traditional predictive models of biomass and volume. However, because the diameter of a tree can generally be modelled as a function of tree height and that tree height measurements can be accurately derived from LiDAR, stand biomass and gross-merchantable volume can be indirectly modelled using LiDAR tree heights.

The Canopy Volume Method (CVM) is a novel method for the description of forest canopies, specifically the physical structure of the canopy (Lefsky *et al*., 1997, 1999b) using full-waveform SLICER data. The principle is to transform the waveform into a canopy height profile and then, using a threshold, classify the profile into four zones: (i) empty, which includes no canopy or ground material; (ii) euphotic, which contains elements in the uppermost 65% of the canopy closure; (iii) oligophotic, which constitute the remaining elements not included in the euphotic or empty zone; and (iv) open gap volume (added to each waveform and represents the difference in space between a waveform and the maximum waveform height considered for a study plot). Subsequently, total volume for each of the four zones can be calculated for a set of waveforms in a study plot.

By plotting the volume of each class against height, Lefsky *et al*. (1997) demonstrate how Douglas-fir/western hemlock stands of differing age can be distinguished from one another based on the vertical distribution of the four canopy classes. Lefsky *et al*. (1999b), using the CVM, demonstrate that nonasymptotic predictions of biomass up to 1200 Mg ha^{-1} and LAI up to 12 could be made and that 90% and 75% of the variance could be explained for biomass and LAI, respectively. More importantly, Lefsky *et al*. (1999b) represent the first study that successfully estimated mean diameter at breast height (DBH) and the number of stems greater than 100 cm in diameter in a set of study plots.

Establishing relationships between LiDAR measurements of forest attributes with corresponding ground measurements has been difficult in tropical forests, given the complexity of the forest structure (Nelson *et al*., 1997). However, Drake *et al*. (2001)

demonstrated that the height of median energy (HOME) LiDAR metric was strongly correlated with basal area and quadratic mean stem diameter using LVIS data collected in Central America. However, the HOME metric differed significantly from above-ground biomass estimates derived from allometric equations. Despite the complexity of tropical forests, the potential of full waveform LiDAR to estimate forest structural parameters is evident.

IV The future of LiDAR for forestry

The potential of LiDAR as a forest inventory and sampling tool has been demonstrated. Although LiDAR technology has matured and large-area land inventories are now being carried out, the required knowledge and techniques to process LiDAR data for applications in forestry is not sufficiently developed for direct application by the forest industry.

In general, the theoretical understanding of the relationships that exist between forest structure and LiDAR response is still incomplete. Apart from the work of Magnussen and Boudewyn (1998) and Magnussen *et al*. (1999) for discrete return systems, and the work of Roberts (1998), Sun and Ranson (2000), and Ni-Meister *et al*. (2001) on full waveform, most of the research is of an empirical nature. A better theoretical understanding could help guide algorithm development for improved forest parameter estimation based on accurate classification of LiDAR canopy and ground hits.

In addition, certain aspects of LiDAR have remained undeveloped. For example, little emphasis has been placed on how the intensity component of the laser return signal can be used as a source of information for forestry. Schreier *et al*. (1985) reported how reflectivity from a laser with a wavelength of 904 nm could be used to discriminate between different types of vegetation cover. Using (i) mean reflection as a percentage of the total sum; (ii) reflection variability expressed as a percent coefficient of variation; and (iii) mean height as a percentage of the total sum as parameters for a ternary diagram, they demonstrated that the space in the ternary diagram in which coniferous forests occurred was distinct from other classes, such as broadleaf forests and ground-cover vegetation. These results imply that the intensity of the laser return signal can be used for classification purposes.

Data fusion between LiDAR data and other image sources is becoming a research topic in itself. Some studies concern the simultaneous use of LiDAR and multispectral images (Hudak *et al*., 2001) while others consider the combination of three-dimensional information obtained from LiDAR and standard photogrammetric techniques (St-Onge and Achaichia, 2001). Combining the three-dimensional LiDAR information to two-dimensional spectral information for forest inventory and mapping is certainly an area of significant potential.

The use of LiDAR in ecological studies has begun to slowly emerge in the literature. Spatial patterns of forest canopies have been explored using multifractal analysis of LiDAR and ground-based canopy heights by Drake and Weishampel (2000) and are of significance to scientists investigating scaling issues. Their multifractal analysis revealed the existence of local differences, or fine-scale patterns, within adjacent transects surveyed with the same technique (e.g., LiDAR). Weishampel *et al*. (2000)

investigated the spatial patterns of LiDAR returns derived from LVIS in an old-growth tropical forest using a lacunarity algorithm and found spatial patterns of the returns to be isotropic and exhibit fractal properties of self-similarity. Without question, more landscape ecology studies based on LiDAR data will be reported in the literature in the near future.

Current research by Japanese researchers involves the development of laser-induced fluorescence (LIF) imaging LiDAR for forestry applications. According to Saito *et al.* (2000: 129), 'LIF imaging LiDAR was developed to monitor and measure the chemical activities and status of trees and forests'. In contrast to studies presented here, their focus of LiDAR for forestry is not on how LiDAR can be used as an inventory and sampling tool, but rather how it can be used as a tool to monitor and assess forest ecosystem health. Results from Saito *et al.* (2000) demonstrate the capability of LIF imaging LiDAR to estimate chlorophyll concentrations in leaves and the potential to carry out surveys at a landscape scale.

Finally, the evolution of LiDAR technology will continue to enhance data quality and richness. Pulse repetition rates and flying heights will continue to increase, allowing for denser and more cost-effective surveys. Automated co-registration of concomitant LiDAR and photographic data will enhance data fusion.

V Conclusion

LiDAR remote sensing is a maturing and expanding technology. It is clear that applications for LiDAR in forestry will continue to increase. Pulse rates and resolution may become more adaptive in terms of footprint size and spacing according to the type of terrain being mapped. System accuracy will increase for higher flying altitudes for larger area coverage. Finally, LiDAR systems will likely become integrated with digital cameras, creating an effective fusion with photogrammetry. Similarly, a fusion between geometric laser scanning and multispectral imaging systems can be expected to make up for the lack of multispectral information currently available from stand-alone LiDAR systems. Therefore, by integrating LiDAR systems with imaging sensors, more robust systems will emerge, thereby satisfying the wide range of data requirements of the forest practitioner at local and regional scales.

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References

Aldred, A. and **Bonner, M.** 1985: *Application of airborne lasers to forest surveys*. Canadian Forestry Service, Petawawa National Forestry Centre, Information Report PI-X-51, 62 pp.

Arp, H., Griesbach, J. and **Burns, J.** 1982: Mapping in tropical forests: a new approach using the laser APR. *Photogrammetric Engineering and Remote Sensing* 48, 91–100.

Axelsson, P. 1999: Processing of laser scanner data–algorithms and applications. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 138–47.

Baltsavias, E.P. 1999a: Airborne laser scanning: basic relations and formulas. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 199–214.

—— 1999b: Airborne laser scanning: existing systems and firms and other resources. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 164–98.

—— 1999c: A comparison of between photogrammetry and laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 83–94.

Blair, J.B., Coyle, D.B., Bufton, J.L. and **Harding, D.J.** 1994: Optimization of an airborne laser altimeter for remote sensing of vegetation and tree canopies. In *Proceedings, International Geoscience and Remote Sensing Symposium*, Pasadena CA, 8–12 August, 939–41.

Blair, J.B., Rabine, D.L. and **Hofton, M.A.** 1999: The Laser Vegetation Imaging Sensor: a medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 115–22.

Cowen, D.J., Jensen, J.R., Hendrix, C., Hodgson, M.E. and **Schill, S.R.** 2000: A GIS-assisted rail construction econometric model that incorporates LiDAR data. *Photogrammetric Engineering and Remote Sensing* 66, 1323–28.

Davenport, I.J., Bradbury, R.B., Anderson, G.Q.A., Hayman, G.R.F., Krebs, J.R., Mason, D.C., Wilson, J.D. and **Veck, N.J.** 2000: Improving bird population models using airborne remote sensing. *International Journal of Remote Sensing* 21, 2705–17.

Drake, J.B. and **Weishampel, J.F.** 2000: Multifractal analysis of canopy height measures in a longleaf pine savanna. *Forest Ecology and Management* 128, 121–27.

Drake, J.B., Dubayah, R., Knox, R.G., Clark, D.B. and **Condit, R.** 2001: Relationship between lidar metrics and aboveground biomass in closed-canopy neotropical forests. In Hofton, M.A., editor, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*. Volume XXXIV, Part 3/W4, Commission III, Annapolis MD, 22–24 October, 147–54.

Dubayah, R.O. and **Drake, J.B.** 2000: Lidar remote sensing for forestry. *Journal of Forestry* 98, 44–46.

Dubayah, R., Blair, J.B., Bufton, J.L., Clark, D.B., JaJa, J., Knox, R., Luthcke, S.B., Prince, S. and **Weishampel, J.** 1997: The vegetation canopy LiDAR mission. In *Proceedings, American Society for Photogrammetry and Remote Sensing*. Washington DC, 5–7 December.

Flood, M. and **Gutelius, B.** 1997: Commercial implications of topographic terrain mapping using scanning airborne laser radar. *Photogrammetry Engineering and Remote Sensing* LXIII, 327–29; 363–66.

Harding, D., Blair, J., Rabine, D. and **Still, K.** 2000: *SLICER airborne laser altimeter characterization of canopy structure and sub-canopy topography for the BOREAS Northern and Southern Study Regions: Instrument and Data Product Description*. In Technical Report Series on the Boreal Ecosystem–Atmosphere Study (BOREAS), Volume 93, 45 pp.

Harding, D.J., Lefsky, M.A., Parker, G.G. and **Blair, J.B.** 2001: Laser altimeter canopy height profiles: methods and validation for closed-canopy, broadleaf forests. *Remote Sensing of Environment* 76, 283–97.

Hickman, G.D. and **Hogg, J.E.** 1969: Application of an airborne pulsed laser for near-shore bathymetric measurements. *Remote Sensing of Environment* 1, 47–58.

Hudak, A.T., Lefsky, M.A. and **Cohen, W.B.** 2001: Integration of lidar and Landsat ETM data. In Hofton, M.A., editor, *The international archives of the Photogrammetry, Remote Sensing and Spatial Information Science*. Volume XXXIV, Part 3/W4, Commission III, Annapolis MD, 22–24 October, 95–104.

Kilian, J., Haala, N. and **Englich, M.** 1996: Capture and evaluation of airborne laser scanner data. In *International Archives of Photogrammetry and Remote Sensing*. Volume XXXI, Part B3, Vienna, Austria, 9–19 July, 383–88.

Krabill, W.B., Collings, J.G., Swift, R.N. and **Butler, M.L.** 1980: *Airborne laser topographic mapping results from Initial Joint NASA/U.S. Army Corps of Engineers Experiment*. NASA Technical Memorandum 73287, Wallops Flight Center.

Krabill, W., Thomas, R.H., Martin, C.F., Swift, R.N. and **Frederick, E.B.** 1995: Accuracy of airborne laser altimetry over the Greenland ice sheet. *International Journal of Remote Sensing* 16, 1211–22.

Kraus, K. and **Pfeifer, N.** 1998: Determination of terrain models in wooded areas with airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing* 53, 193–203.

Kreslavsky, M. and **Head, J.** 1999: Kilometer-scale slopes on Mars and their correlation with geologic units: initial results from Mars Orbiter Laser Altimeter (MOLA) data. *Journal of Geophysical Research* 104, 21911–24.

Lefsky, M.A., Cohen, W.B., Acker, S.A., Spies, T.A., Parker, G.G. and **Harding, D.** 1997: Lidar remote sensing of forest canopy structure and related biophysical parameters at the H.J. Andrews Experimental Forest, Oregon, USA. In Hofton, M.A., editor, *Natural Resources Management Using Remote Sensing and GIS*. Washington DC: ASPRS, 79–91.

Lefsky, M.A., Harding, D., Cohen, W.B., Parker, G. and **Shugart, H.H.** 1999a: Surface LiDAR remote sensing of basal area and biomass in deciduous forests of Eastern Maryland, USA. *Remote Sensing of Environment* 67, 83–98.

Lefsky, M.A., Cohen, W.B., Acker, S.A., Parker, G.G., Spies, T.A. and **Harding, D.** 1999b: Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forests. *Remote Sensing of Environment* 70, 339–61.

Lefsky, M., Cohen, W. and **Spies, T.** 2001a: An evaluation of alternate remote sensing products for forest inventory, monitoring, and mapping of Douglas-fir forests in western Oregon. *Canadian Journal of Forest Research* 31, 78–87.

Lefsky, M.A., Cohen, W.B., Harding, D.J., Parker, G.G., Acker, S.A. and **Gower, S.T.** 2001b: Lidar remote sensing of aboveground biomass in three biomes. In *The international archives of the photogrammetry, remote sensing and spatial information science*. Volume XXXIV, Part 3/W4, Commission III, Annapolis MD, 22–24 October, 155–60.

MacLean, G.A. and **Krabill, W.B.** 1986: Gross-merchantable timber volume estimation using an airborne LiDAR system. *Canadian Journal of Remote Sensing* 12, 7–18.

MacLean, G.A. and **Martin, G.L.** 1984: Merchantable timber volume estimation using cross-sectional photogrammetric and densitometric methods. *Canadian Journal of Forest Research* 14, 803–10.

Magnussen, S. and **Boudewyn, P.** 1998: Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators. *Canadian Journal of Forest Research* 28, 1016–31.

Magnussen, S., Eggermont, P. and **LaRiccia, V.N.** 1999: Recovering tree heights from airborne laser scanner data. *Forest Science* 45, 407–22.

Matrosov, S., Heymsfield, A., Kropfli, R., Martner, R., Reinking, R., Snider, J., Piironen, P. and **Eloranta, E.** 1998: Comparison of ice cloud parameters obtained by combined remote sensor retrievals and direct methods. *Journal of Atmospheric and Oceanic Technology* 15, 184–96.

McArdle, S.S., Farrington, G. and **Rubinstein, I.** 1999: A preliminary comparison of flood risk mapping using integrated remote sensing technology to aerial photography. In *Proceedings, Fourth International Airborne Remote Sensing Conference and Exhibition*. Ottawa, Ontario, 21–24 June. Ann Arbor MI: ERIM International, 616–23.

Means, J. 1999: Design, capabilities and uses of large-footprint and small-footprint lidar systems. In Csathó, B.M., editor, *International Archives of the Photogrammetry and Remote Sensing*. Volume 32, Part 3-W14, La Jolla, California, 9–11 November, 201–207.

Means, J.E., Acker, S.A., Harding, D.J., Blair, D.B., Lefsky, M.A., Cohen, W.B., Harmon, M.E. and **McKee, W.A.** 1999: Use of large-footprint scanning airborne LiDAR to estimate forest stand characteristics in the Western Cascade of Oregon. *Remote Sensing of Environment* 67, 298–308.

Nelson, R. 1997: Modeling forest canopy heights: The effects of canopy shape. *Remote Sensing of Environment* 60, 327–34.

Nelson, R., Krabill, W. and **Maclean, G.** 1984: Determining forest canopy characteristics using airborne laser data. *Remote Sensing of Environment* 15, 201–12.

Nelson, R., Krabill, W. and **Tonelli, J.** 1988a: Estimating forest biomass and volume using airborne laser data. *Remote Sensing of*

Environment 24, 247–67.

Nelson, R., Swift, R. and **Krabill, W.** 1988b: Using airborne lasers to estimate forest canopy and stand characteristics. *Journal of Forestry* 86, 31–38.

Nelson, R., Oderwald, R. and **Gregoire, T.G.** 1997: Separating the ground and airborne laser sampling phases to estimate tropical forest basal area, volume, and biomass. *Remote Sensing of Environment* 60, 311–26.

Neumann, G.A. 2001: Aspects of processing extra-terrestrial lidar data: Clementine, NEAR, MOLA. In Hofton, M.A., editor, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*. Volume XXXIV, Part 3/W4, Commission III, Annapolis MD, 22–24 October, 73–80.

Næsset, E. 1997: Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing* 52, 49–56.

Ni-Meister, W., Jupp, D.L.B. and **Dubayah, R.** 2001: Modeling lidar waveforms in heterogeneous and discrete canopies. *IEEE Transactions on Geoscience and Remote Sensing* 39, 1943–58.

Nilsson, M. 1996: Estimation of tree heights and stand volume using an airborne LiDAR system. *Remote Sensing of Environment* 56, 1–7.

Parker, G.G., Lefsky, M.A. and **Harding, D.J.** 2001: Light transmittance in forest canopies determined using airborne laser altimetry and in-canopy quantum measurements. *Remote Sensing of Environment* 76, 298–309.

Ritchie, J.C., Evans, D.L., Jacobs, D., Everitt, J.H. and **Weltz, M.A.** 1993: Measuring canopy structure with an airborne laser altimeter. *Transactions of the ASAE* 36, 1235–38.

Roberts, G. 1998: Simulating the vegetation canopy lidar: an investigation of the waveform information content. University College London, M.Sc. Thesis, 74 pp.

Saito, Y., Saito, R., Kawahara, T.D., Nomura, A. and **Takeda, S.** 2000: Development and performance characteristics of laser-induced fluorescence imaging LiDAR for forestry applications. *Forest Ecology and Management* 128, 129–37.

Schreier, H., Lougheed, J., Tucker, C. and **Leckie, D.** 1985: Automated measurements of terrain reflection and height variations using an airborne infrared laser system. *International Journal of Remote Sensing* 6, 101–13.

St-Onge, B.A. and **Achaichia, N.** 2001: Measuring forest canopy height using a combination of lidar and aerial photography data. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*. Volume XXXIV, Part 3/W4, Commission III, Annapolis MD, 22–24 October, 131–38.

St-Onge, B., Dufort, J. and **Lepage, R.** 2000: Measuring tree height using scanning laser altimetry. In *Proceedings of the 22nd Annual Canadian Remote Sensing Symposium*. Victoria, B.C., 21–25 August, 425–32.

Sun, G. and **Ranson, K.J.** 2000: Modeling lidar returns from forest canopies. *IEEE Transactions on Geoscience and Remote Sensing* 38, 2617–26.

Tickle, P., Witte, C., Danaher, T. and **Jones, K.** 1998: The application of large-scale video and laser altimetry to forest inventory. In *Proceedings of the 9th Australasian Remote Sensing and Photogrammetry Conference*. Sydney, Australia, 20–24 July.

Tickle, P.K., Witte, C., Lee, A., Jones, K., Denham, R., Lucas, R.M. and **Austin, J.** 2001: The use of airborne scanning Lidar and large scale photography within a strategic forest inventory and monitoring framework. In *Proceedings, International Geoscience and Remote Sensing Symposium*, Sydney, Australia, 9–13 July.

Walklate, P.J., Richardson, G.M., Baker, D.E., Richards, P.A. and **Cross, J.V.** 1997: Short-range LiDAR measurement of top fruit tree canopies for pesticide applications research in the UK. In Narayanan, R.M. and Kalshoven, J.E., Jr, editors, *Proceedings of SPIE – Advances in Laser Remote Sensing for Terrestrial and Oceanographic Applications*. Orlando, FL, 21–22 April, Washington DC: The International Society for Optical Engineering, 143–51.

Wehr, A. and **Lohr, U.** 1999: Airborne laser scanning – an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, 68–82.

Weishampel, J.F., Ranson, K.J. and **Harding, D.J.** 1996: Remote sensing of forest canopies. *Selbyana* 17, 6–14.

Weishampel, J.F., Blair, J.B., Knox, R.G., Dubayah, R. and **Clark, D.B.** 2000: Volumetric LiDAR return patterns from an old-growth tropical rainforest canopy. *International Journal of Remote Sensing* 21, 409–15.

Wulder, M. 1998: Optical remote-sensing techniques for the assessment of forest inventory and biophysical parameters. *Progress in Physical Geography* 22, 449–76.

Wulder, M., Magnussen, S., Harding, D., Boudewyn, P. and **Seemann, D.** 2000: Stability of surface LiDAR height estimates on a point and polygon basis. In *Proceedings of the 22nd Annual Canadian Remote Sensing Symposium*. Victoria, British Columbia, 21–25 August, 433–38.

Young, M. 1986: *Optics and lasers: including fibers and optical waveguides*. Berlin: Springer Verlag.