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Chapter 19

TREE AND CANOPY HEIGHT ESTIMATION WITH SCANNING LIDAR

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1. INTRODUCTION

A large part of the research efforts concerning the remote sensing of forests has been devoted to the development of repeatable methods for the extraction of information from monoscopic, two-dimensional images. Emphasis has been on spectral pattern recognition. Although appropriate for species or health characterisation, this approach comes with several limitations when detailed information on forest structure, e.g. three-dimensional aspects of forest canopies, is sought (Wulder 1998). Accurate measurements of height, density, volume, stratification, etc. at local scales, which are of prime interest for foresters and forest ecologists, and which have a geometric rather than radiometric nature, are still beyond the capabilities of two-dimensional remote sensing and image processing.

Three-dimensional remote sensing is a promising and fast growing field, and has already proven more accurate than spectral remote sensing for certain attributes (Hyyppä et al. 2000; Lefsky et al. 2001). Recent technological advances allow efficient soft copy photogrammetry, precise radar interferometry, and laser altimetry. Out of these three technologies, laser altimetry shows the best performance in producing three-dimensional data on both ground and canopy topography (Baltsavias 1999; Hyyppä et al.

2000; Hese and Lehman 2000). In particular, the ability of laser altimeters to penetrate forest canopies through to ground level presents new possibilities, such as mapping canopy height with high precision and accuracy.

Light Detection and Ranging (lidar) is a common research technique used in a variety of application areas including atmospheric research, chemical analysis and monitoring and distance measuring. When deployed as a remote sensing tool from airborne or spaceborne platforms it is referred to as laser altimetry. In common practise laser altimetry is performed using an active sensor that combines a high frequency pulsed laser (the transmitter) with a telescope and solid state photo-detector (the receiver). A portion of the incident laser pulse energy is reflected back to the sensor from each intercepted surface and the round trip travel time between the transmitted and reflected laser pulses between the airborne sensor and the target surface is converted to a range distance. In post-processing this range measurement is combined with synchronised platform position data from a precise differential GPS solution and platform orientation information from an on-board inertial navigation system (INS) to compute the position of the lidar echo, or "pulse return", from each terrestrial target.

Scanning the field of view of the sensor perpendicular to the flight path of the aircraft during flight provides greater swath coverage and more efficient data collection than a simple profiling system but introduces some complexities due to off-nadir look angles. The absolute elevation accuracy of the lidar data is typically 10-40 cm from a flying height of 1000 m for scanning lidar systems (Baltsavias 1999).

There are two distinct types of lidar systems in the commercial and research sectors: full waveform and discrete return. In the first case, the returned laser energy is densely sampled over a short time interval using an on-board high sampling rate signal digitizer to create a "full waveform" description, i.e. amplitude over time, of the return signal from a single pulse. This full waveform describes the energy intensity reflected back towards the sensor by the different strata of the vegetation column traversed by the pulse. It is a function of foliage density and structure (i.e. clumping, gaps) throughout the column (Ni-Meister 2001).

Discrete return lidar systems, on the other hand, typically record only the occurrence of first and last returns from a series of returns corresponding to discrete surfaces along the slant range. That is, they do not sample the full return signal waveform but rather record the time-of-flight (range) to the peak of any signal that exceeds the noise threshold. Sample and hold techniques are used to capture the last return of a series of returns when the vertical profile of the target is complex.

In a forest environment, the first return corresponds to the initial amplitude rise over the background noise level caused by the energy echoed by the outer vegetation layer of a canopy. The last return corresponds to the last detectable signal above the noise threshold from a series of returns, at some time interval after the first return, when the pulse is intercepted by an opaque object, normally the ground. Last returns are (post-flight) classified such that "true" ground returns are separated from low vegetation returns. Some discrete-return lidar systems are now capable of recording up to five returns.

The majority of discrete return sensors in use today are built using solid-state, diode-pumped lasers that operate at near infrared wavelengths, ~ 1 μm, with pulse repetition rates from 5,000 to 35,000 Hz and pulse energies in the order of 100s of μJ.

Full waveform lidar systems, such as SLICER (e.g. Means et al. 1999) are generally profiling systems (with one to a few parallel profiles) and have only been used for research purposes. Discrete return scanning lidar systems are used commercially for topographic mapping, including wide area surveys (Hill et al. 2000). While the former have a large diameter footprint (several meters wide), discrete return lidar systems typically possess footprints of less than a metre in diameter. Even though only a fraction of all pulses reach ground level, the sampling of ground elevation remains sufficiently dense to allow for development of precise below-canopy digital elevation models (Kraus and Pfeifer 1998).

Due to their commercial availability (as opposed to full-waveform systems) and their mapping capabilities, the following discussion on lidar for forest attribute estimation will concentrate on the application of discrete return lidar systems. For detailed reviews of lidar technology and applications for forestry, the reader is referred to Wehr and Lorh, (1999), and Lim et al. (2002). The reader is also referred to Lefsky et al. (2001) and Harding et al. (2001) for examples of full waveform lidar applications for the study of forest canopies.

Here we discuss the methods used to produce, pre-process, and analyse discrete return scanning lidar data. We will review several methodological details that are critical to the success of a lidar mission for forestry and subsequent analyses. We begin, however, by presenting a brief review of forestry applications of lidar to give a general idea of the current status.

Subsequent sections include: methodological considerations pertaining to the acquisition of lidar data; pre-processing and analysis of lidar data for the extraction of forest information, specifically what we consider the most suitable methods for the estimation of stand height and individual tree height. For brevity, we have omitted detailed methodological considerations related to other forest attributes such as timber volume, biomass, density, etc. Our focus on height is motivated by the importance of this parameter for estimating other forest attributes, in particular volume and biomass. To ensure completeness, the following overview section includes, where appropriate, attributes other than height.

2. THE STUDY OF FORESTS USING LIDAR

Lidar systems were first tested as remote sensing tools for topography and bathymetry in the 1960s (see Aldred and Bonnor 1985, for a review of early systems). The use of lidar for forest applications was first investigated in the 1970s (Soludukin 1977 cited in Nelson et al. 1997). Interest in the accurate estimation of stand height, volume, and biomass developed as early as the 1980s, when it was demonstrated that mean stand height estimates produced using lidar were as accurate as ground or standard photogrammetric measurements (Schreier et al. 1985; Aldred and Bonnor 1985).

Success in estimating timber volume and biomass was also achieved early. For example, MacLean and Krabill (1986) obtained high coefficients of determination ($0.72 \leq r^2 \leq 0.89$) for predictive models of volume.

Until 1993, the vast majority of forest studies using lidar were carried out with profiling systems, using either full waveform or discrete return approaches. Because the Global Positioning System (GPS) was not yet fully developed at the time, locating the lidar trace on the ground was problematic. Since the mid-nineties, several researchers have tested lidar scanners equipped with precision GPS and Inertial Navigation Systems (INS), also referred to as internal measurement units (IMUs). Estimates of stand height and volume comparable to those obtained using profilers have been achieved consistently (e.g. Nilsson 1996; Næsset 1997; St-Onge and Renaud 2000; Næsset 2002).

The return density of current scanning lidar systems enables the resolving of individual tree crowns, which allows for the estimation of individual tree heights (St-Onge et al. 1999; Lim et al. 2001; Persson et al. 2002). Methods for extracting tree and forest stand data will continue to improve through a better theoretical understanding of the lidar response of forest canopies.

As well as stand height and volume, other forest attributes are being studied, notably biomass and vertical foliage distribution. Most of these studies were performed using full waveform lidar systems (e.g. Lefsky et al. 1999).

3. LIDAR SURVEY SPECIFICATIONS

No systematic satellite lidar data acquisition programs comparable to Landsat in the field of multi-spectral imagery currently exist. Lidar space missions are planned, however, for instance the Geoscience Laser Altimeter System (GLAS) (Carabajal and Harding 2001), and the Vegetation Canopy Lidar (VCL) (Dubayah et al. 1997; Luthcke and Rowlands 2001).

The acquisition of lidar data from airborne platforms (light aeroplanes or helicopters) requires input parameter specifications for both the lidar instrument and the flight configuration, in order to achieve the desired sampling pattern. For this reason, users specify lidar survey acquisition parameters in consultation with the survey provider. It is therefore essential that the user understand the implications of flight and acquisition parameters for the quality and usefulness of the lidar data collected for their application.

In this section, we provide a summary of the key parameters to consider and present a few principles for adequately matching needs and specifications.

3.1 Platforms

Current lidar missions are performed using small aircraft operating at low altitudes. While small aeroplanes and helicopters are regularly used, the former tend to be used more frequently. Each platform possesses certain advantages and disadvantages. Aeroplanes tend to provide better pitch and yaw stability, which translates into more regular flight lines with fewer gaps between adjacent flight lines. Helicopters provide slower air speeds, a factor that is very useful in providing a high density of pulse returns. Some lidar systems can be quickly attached to standard helicopters, such as the ALMIS-350 operated by Mosaic Mapping Systems Inc. (Ottawa). The ALTM series of instruments from Optech can be mounted on an aeroplane or helicopter and offers roll compensation.

3.2 Flight altitude

The flight altitude interval of current lidar systems is quite narrow. The minimum altitude at which the sensor can be operated is governed by eye safety regulations; this varies from design to design but a good rule-of-thumb is approximately 500 m above ground level (AGL)). At the higher end, the power of the laser and the peak pulse energy become the limiting factors, as sufficient energy must reach ground level for a clear return to be detected and recorded. In addition, intervening cloud cover becomes an issue at higher altitudes as, unlike radar sensors, lidar systems cannot penetrate clouds, thus limiting the available data collection hours in areas where low-lying clouds are an issue.

For commercial sensors, the maximum operating altitude is 6000 m, but in practice most systems are limited to 2000 m AGL. Research systems such as NASA's LVIS sensor operate at higher altitudes, up to 8,000 m, although this is a waveform capture design (Blair et al. 1999). It is also important to note that with all other parameters held constant, the return density, i.e. the number of laser echoes recorded per unit area, decreases as altitude is increased. Technological developments will no doubt help raise this maximum altitude.

Meanwhile, low flight altitude and near vertical incidence angles make for narrow swath widths, numerous flight lines, and relatively high costs, but, when paired with a high repetition rate sensor, allow for extremely high-density data collection (multiple returns per sq. m).

3.3 Flying speed

While minimum and maximum flying speeds are normally limited by the aircraft's design specifications, other considerations such as the pattern of laser returns on the ground are equally important. The return density is typically much higher along the scan lines (cross-track) than along the flight path (along-track). Flying at too great a speed will increase the discrepancy between the along- and across-track target pulse return densities. The gap between two consecutive scan lines at nadir could reach such a size that many trees would be omitted from the along-track direction (Evans et al. 2001), even though individual trees could be resolved in the across-track direction. If the aim is an ideal isotropic return density, then altitude, speed, pulse frequency, scan width and scan frequency must be considered and adjusted as a set. In addition, the scan pattern produced by the sensor must be considered.

The majority of commercial sensors employ a single axis scanning mirror driven by a galvanometer that produces a saw-tooth pattern on the ground, but there are sensors that use rotating polygon mirrors to produce equidistant sampling in a well-defined grid. This type of scan pattern can be desirable if isotropic sampling is a primary requirement of the research. Survey providers normally use special software applications to plan missions according to target pulse return densities.

3.4 Divergence and footprint size

Divergence is the rate at which the collimated laser beam's diameter increases with range. It is measured in milliradians (mr) and can be readily converted to footprint diameter using aircraft-to-ground distance. Some recent commercial lidar systems (e.g. Optech ALTM 1225 and 2033) offer two divergence settings.

Footprint size, not divergence *per se*, is the determining factor in forest studies. Two conflicting objectives generally arise when seeking an optimal footprint size. These are: 1) achieving a high penetration rate and a high spatial resolution; and 2) hitting tree apices as often as possible. The first goal demands a small footprint while the second imposes a larger footprint size. The decreased probability of hitting tree apices with a very small footprint size tends to be compensated for with very high pulse return densities.

While footprint size does affect data characteristics, it does not greatly influence the accuracy of canopy height measurement within the most commonly applied range of settings, at least when using nadir viewing profilers (Aldred and Bonnor 1985). Footprint size will impact the horizontal accuracy (XY position) of the data due to spatial ambiguity within the footprint; increasing footprint size will increase this ambiguity. However for most small footprint (< 1 m) sensors this is not a major error contributor. Moreover, the narrow flying altitude intervals and rigid system settings do not permit much flexibility in footprint size. However, next-generation sensors already under development should increase the options in this area.

3.5 Pulse frequency

Pulse frequency is a characteristic of the pulsed laser itself. Technological improvements have brought about a rapid increase in pulse frequency for commercial systems. For example, the ALTM series from Optech has evolved from a 5 kHz frequency for the 1020 model in 1993 to 33 kHz for the 2033 model in 2001. Development is continuing, with 50 kHz sensors being field tested and due to be online by mid 2002 while some studies have predicted 100 kHz sensors will be available by 2005 (Flood 2001). Surveys are generally conducted with the pulse frequency set to maximum. However, optimal lidar sampling theory for forest studies has yet to be fully developed.

Improvement in pulse frequency enables more cost effective data acquisition on a per unit basis since flying height, within a modest range, can be increased as pulse return density improves. It also allows denser sampling for a low flying aircraft, which means that commercial lidar systems can now achieve several pulse returns per square meter. This in turn opens up new research possibilities, as ever-smaller individual tree crowns can be sampled. Increased pulse density also allows for better fidelity of ground models as increased pulse rates will increase the number of pulses that pass through the canopy to the ground. This can be of increasing importance when dealing with very closed canopy or where there is significant understorey or ground cover.

3.6 Scan frequency, swath width, and overlap

The typical single axis oscillating mirror design results in a saw-tooth scan pattern. In order to maximize lidar energy penetration through vegetation cover to the ground level, it is preferable to limit incidence angles to 15-20 degrees off nadir. Penetration improves as the scan approaches nadir. Due to low flying altitudes and near vertical viewing angles, swath width is generally quite low (e.g. 115 m), but can be as wide as 2,180 m (Optech 2001). Swath width and scan frequency can be adjusted concurrently with altitude, aircraft speed and pulse frequency to produce, on average, anisotropic return densities. Optech's ALTM 2033 (released in 2001) has a maximum scan frequency of 90 Hz. If the lidar systems and flying parameters are set to: (i) full pulse frequency (i.e. 33 kHz) (ii) typical flying speed of 64 m/s; (iii) flying altitude of 500 m, (iv) scan frequency of 66 Hz; and (v) swath width of 115 m , an average posting distance (i.e. the distance between two consecutive pulse returns) of 0.48 m will result (Optech 2001). Sensors based on rotating polygon mirrors provide a much more regular grid pattern but require a more complex receiver design and so are less common in commercial use.

Swath overlap, or inter-flight line distance, should be set in such a way that the probability of gaps appearing between swaths is minimized. Large variations in return density for overlapping and non-overlapping regions of the survey can result in inconsistencies in data processing. To alleviate this problem, it is often recommended to set a goal of 50 % overlap between flight lines. This will not only double the return density, but will provide for a more even distribution of returns. Sensors that include roll stabilisation or a fully stabilised mount can usually reduce this overlap to 25 % - 35 % while maintaining full coverage. Flying twice to increase the density can also be considered. When possible, it is preferable to lay out the second pass flight lines perpendicularly to that of the first one (e.g. Næsset 2002).

4. LIDAR DATA CHARACTERISTICS AND QUALITY

4.1 Composition of lidar datasets

A discrete scanning lidar dataset is minimally composed of X,Y,Z triplets representing the location of each recorded echo for at least the first or last return from the emitted pulse. These data are generally delivered in ASCII files; however a major industry initiative was started in 2002 to adopt a common binary format for the delivery and exchange of lidar data. When implemented, this initiative should improve the accessibility of lidar data by reducing file sizes and providing a common exchange format, while also promoting the development of third-party software tools for data analysis and manipulation.

Currently, lidar data sets require interpolation if a continuous grid representation is desired. Most current lidar systems capture a first and last return for each pulse. While these are often divorced in typical data products because the bulk of lidar users are solely interested in ground returns for topographical purposes, there are advantages to retaining the two triplets representing the first and last returns in the same ASCII record. Several uses can be made of this pairing. For example, the depth of the traversed vegetation column (i.e. Z_{first}-Z_{last}), and/or the occurrence of bare ground (i.e. $Z_{first} = Z_{last}$) can be determined. Moreover, as mentioned above, we see more lidar systems that record the intensity (I) of the return energy. These values are normally proportional to the reflectance of surfaces. However, incidence angle effects on the footprint size and on the specular reflection component can also affect the quantity of returned energy. Intensity measurements can help in discriminating between deciduous and coniferous trees, with the return intensity being a function of the nature of the reflecting surface and the wavelength and angle of incidence of the emitted lidar signal. However, the algorithms used to trigger first and last pulse recordings based on characteristics of the return signal may also affect the intensity value, as do variations in the transmitted pulse energy. It would be desirable that lidar manufacturers publish these algorithms and explicate how the radiance measured by the sensor is normalised (or not) and converted to digital numbers.

4.2 Spatial resolution and accuracy

Spatial resolution for typical remotely sensed data is dependent upon the size of the instantaneous field of view (IFOV). In the case of lidar, spatial resolution is determined by: (i) the footprint size; and (ii) the posting distance. This latter parameter is the primary factor defining spatial resolution for interpolated lidar elevation or intensity surfaces. Spatial resolution is used here to designate the extent to which details of canopy surface topography can be resolved. Footprint sizes from scanning lidar systems are typically just a few centimetres wide (15-50 cm). If such small footprint pulse returns were touching or overlapping, individual branches could easily be resolved. Normally, the average posting distance is of the order of one to a few meters.

A few important characteristics of the pulse return spatial distribution should be noted. First, laser returns are not evenly distributed over the area surveyed. The scan pattern, the attitude variation of the aircraft, the lost returns due to deflection, the topography of both the terrain and canopy surface, and the random manner in which incident pulses from two adjacent flight lines will criss-cross, all compound to distribute the pulse returns in unpredictable and uncontrollable semi-irregular patterns. Some patches might, for example, receive more than 10 pulse returns/m^2 while areas of several square meters might be devoid of any pulse returns. It is common to report resolution equivalents in the form of pulse return densities or average posting distance rather than in terms of IFOV or true spatial resolution. Rarely do authors state the variations around these average figures or report on the size of the largest lidar gaps. The irregular layout can seriously impact data quality, especially at low pulse return densities. Research on the effects that follow from this disorderliness are just beginning (e.g. Evans et al. 2001).

Lidar is, however, a very accurate instrument. Manufacturers and data providers report absolute elevation accuracies of 15 cm and even better relative accuracies. In the commercial sector, vertical accuracy is generally taken by system manufactures to be a 1σ statistical measure of the sensor's accuracy against a known ground target, while data providers generally quote a 2σ or 95 % confidence level closer to 20 cm. Vertical accuracy of lidar data varies with vegetation cover and topography; in addition, the error budget for a lidar sensor is quite hard to establish (Shenk 2000).

Two sets of factors can affect elevation accuracy: system related and target related. Errors from the lidar system include ranging error, GPS error, timing errors and mounting error, which consists of errors in determining the offset between the onboard GPS antenna and the lidar system itself. By far the largest cause of "bad" lidar datasets is a poor GPS solution. A good GPS solution is a necessary but not sufficient condition if any reasonable accuracy is to be expected from the lidar data; conversely, a poor GPS solution generally degrades the dataset quality, often significantly so. It is critical, when working with lidar data providers, to ensure they implement proper GPS planning (PDOP windows, baseline lengths etc).

Target related errors include slope-induced errors (i.e. error is known to increase with terrain slope), classification errors and uncertainty in precisely defining the first and last return ranges. Of these, classification errors produce the largest discrepancies between "true" and "observed" terrain elevations (see section 5.1). The impact of elevation errors on our capacity to accurately estimate stand height remains to be investigated.

Planimetric (i.e. X, Y) errors are known to be approximately five times greater than their elevation counterpart (Baltsavias 1999). As a rule of thumb, absolute planimetric errors are approximately 1/2000 of the above-ground altitude of the aircraft.

5. LIDAR DATA PRE-PROCESSING

Stages of pre-processing normally required to prepare lidar data for predicting stand parameters include: (i) calculation of a precise platform trajectory from the differential GPS solution; (ii) computation of the X,Y,Z values from in-flight ranging and combined GPS and INS data; (iii) classification of the pulse returns and (iv) interpolation of ground and vegetation returns. The survey provider will deliver X,Y,Z triplets and will very often carry out the classification. However, there are advantages to retaining control over the classification in order to test different classification parameter values.

Most data providers will deliver classified and unclassified datasets if requested. Unfortunately, classification software, such as Optech's REALM™ (Optech Inc., Toronto, Canada) or TerraScan™ (TerraSolid Inc., Helsinki, Finland) are proprietary to sensor owners (REALM) or still quite expensive to acquire (TerraScan). Lidar classification functions are not currently part of any common image processing software package, although this functionality will probably become standard over the next few years.

The user most often carries out interpolation of the lidar returns, using either their own code or routines available in the public domain. Here again, control over interpolation methods is preferable. Finally, lidar data volumes are considerable. Relatively modest datasets are composed of millions, or tens of millions of return triplets. A standard desktop computer is not designed to process lidar data in these quantities. Even for small study areas, a workstation with considerable disk capacity (60 GB); RAM (2 GB); and CPU speed (1 GHz) is recommended for efficient processing of lidar data. These requirements will undoubtedly increase as study areas become larger (e.g. for operational surveys) and sample density increases.

5.1 Classification of lidar pulse returns

Classification, also referred to as "filtering", essentially consists of assigning a particular return to ground level or to some other feature on the surface. Most often, it is carried out automatically using classification software, but manual interventions are still required for, among other things, building and vegetation removal. Classification techniques were initially developed in order to produce "bare-earth" digital elevation models (DEMs) and are still being perfected. For forest applications, classification relies on the following simple rationale: the lowest returns in a small neighbourhood will be ground, while the rest will correspond to vegetation, buildings or infrastructure. The approach consists of identifying which returns are most likely to correspond to ground level, and to assume that all other returns correspond to something else. In natural landscapes, these other returns are assumed to be vegetation.

Most classification algorithms use iterative statistical or morphological algorithms operating over window-based kernels. As an example, we describe here the algorithm used by the TerraScan™ software (TerraSolid Ltd., Helsinki, Finland). TerraScan™ is relatively affordable and widespread. The algorithm is published by Axelsson (2000).

After an initial coarse classification to remove gross errors (high and low points, or points outside the known range of expected returns) , the algorithm builds a sparse TIN (Triangulated Irregular Network) from a subset of lidar pulse returns that are considered "sure pulse returns on the ground" (TerraSolid 2001). This initial subset is composed of the lowest points in each cell of a user defined virtual grid that is superimposed onto the dataset. Most triangular facets of this first TIN will be below the ground level. Returns are then added iteratively by selecting new points and rebuilding the TIN, with point selection based on angle and distance thresholds. The angle threshold consists, at the maximum, of the angle formed by a line joining a candidate point to the closest vertex of the facet on which it downwardly projects, and the line joining this vertex to the point projection location on the same facet. It is often suggested that different angle threshold values be used depending on the nature of the topography. The maximum distance threshold controls the single-iteration upward evolution of the TIN by limiting the vertical distance between a candidate point and the surface of the facet on which it vertically projects. The steepest allowable terrain slope also controls the algorithm. We have tested both TerraScan™ and REALM™ on double return data acquired with Optech's ALTM1225. Both software packages classified dense bushes, which were virtually impenetrable by the lidar pulse, as ground. This finding is similar to that of Pfeifer et al. (1999). It led to the presence of conspicuous bumps on the otherwise smooth DEM. It supports our contention that automated classification for DEM generation requires further refinement.

5.2 Interpolating lidar pulse returns

Lidar data is typically composed of millions of X, Y, Z data points. While these can be visualised as point clouds, raster grid representations are usually more readily interpreted. Moreover, measuring tree or canopy heights requires that the elevation difference between the top of canopy and ground level be measured. Theoretically, it is close to impossible for a ground return to be recorded directly under a vegetation return located on a tree apex. For this reason, it is practical, and very common, to interpolate the ground returns to form a DEM. In most cases, TIN or spline interpolation (e.g. Magnussen et al. 1999) is used. Height is then obtained by computing the elevation difference between each vegetation pulse return and the underlying grid cell's elevation. Canopy pulse returns can also be interpolated, but more restrictive conditions apply.

Interpolation of vegetation returns is far more complicated than that of ground returns as the goal is to reconstruct the canopy surface to create a canopy surface model (CSM). Interpolation of the CSM to a raster grid greatly reduces the size of the lidar dataset and also allows for the application of standard raster GIS and remote sensing algorithms. It is our opinion that only very dense lidar vegetation pulse return datasets should be interpolated in this fashion. Once the they are, the interpolated ground can be subtracted from the interpolated canopy to produce a canopy height model in which each pixel represents the height above ground of the canopy. Figure 19-1A gives an example of a canopy height model for a patch of forest also presented on an orthophoto (Figure 19-1B).

6. ESTIMATING CANOPY, STAND, AND INDIVIDUAL TREE HEIGHT

Tree height remains a primary attribute for forest inventory and timber volume estimation (Aldred and Bonner 1985; Schreier et al. 1985) and is one of the main factors determining light interception and inter-tree competition (Sprurr and Barnes 1980). It is therefore not surprising that the estimation of tree and canopy height using lidar data has received more attention than that of any other forest metric. Height estimation methods have been tested at different spatial scales (i.e. individual tree, plot, stand), with relatively positive results. Many authors have reported that lidar underestimates stand height (e.g. Nilsson 1996; Næsset 1997), which is in our opinion, and in light of the theoretical work done by Magnussen and Boudewyn (1998) and Magnussen et al. (1999), a statement which requires qualification.

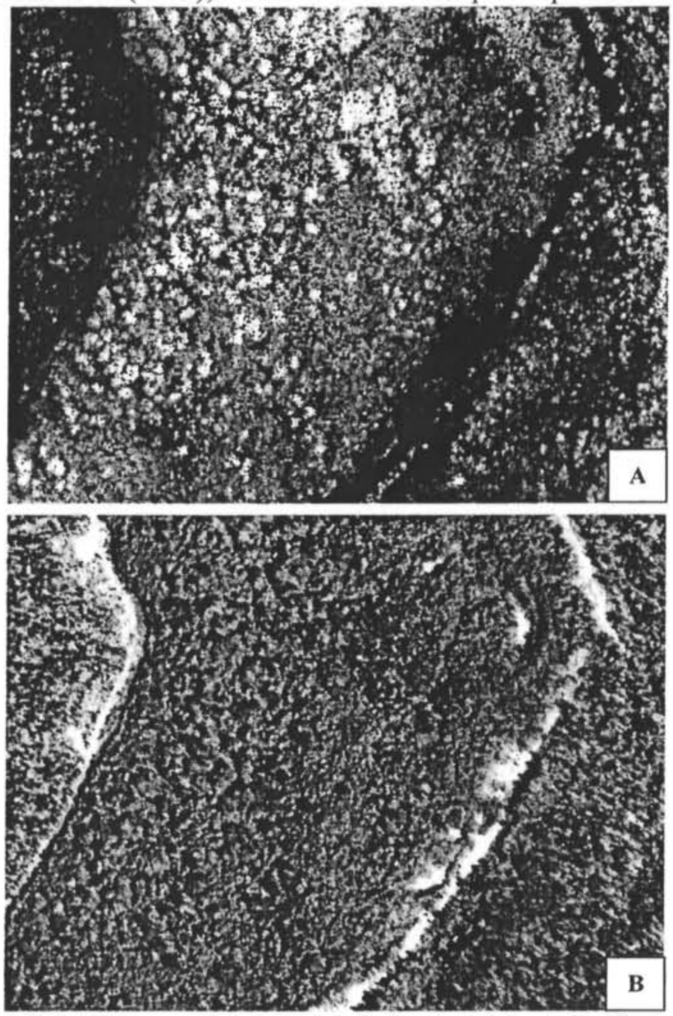


Figure 19-1. Lidar canopy height model of a forest patch located in Green River, New-Brunswick, Canada (with brightness proportional to canopy height) (A), and Orthophoto of the same patch (B).

6.1 Basic concepts and rationale

A tree is a discrete object for which boundaries can be established readily in the field. The height of an individual tree is simply the elevation difference between its ground level base and its apex. What constitutes canopy height or stand height is less straightforward. For clarity, we will use the following concepts: *canopy surface height, mean canopy height, mean tree height* and *Lorey's height*.

Canopy surface height refers to the "outer canopy envelope" containing the underlying vegetation volume. The height of a point on the canopy surface is the length of a vertical line that extends from the idealised canopy surface down to the ground level. We will call this point measure "canopy surface height" or, more simply, "canopy height" after Magnussen and Boudewyn (1998), and Magnussen et al. (1999). In this regard, lidar first returns (minus ground elevation) are considered a sample of the complete canopy height distribution (Magnussen et al. 1999).

Mean canopy height consists of the mean height of all canopy surface points. *Mean tree height* is simply the average height of all trees within a given area, while *Lorey's height* is defined as the basal area weighted average tree height within an area (Næsset 1997).

Having defined the key terms and concepts, we can now state the general problem. We have seen that the sampling pattern of a scanning lidar is semi-random and that only a small fraction of the canopy surface is intercepted by laser pulses. Most pulses miss tree apices. Hence, the average height of lidar (i.e. vegetation) first returns is primarily an estimator of mean canopy height, and can in no way be *directly* related to mean tree height nor Lorey's height. For this reason, it can be misleading to state that "lidar underestimates stand height". This also means that we must find a way to predict, for example, Lorey's height by stand or forest polygon, or individual tree heights, using semi-random point samples of canopy surface height. It translates into a search for a method that can identify the most useful lidar returns and/or an unbiased statistical estimator of tree height, whether at the stand or tree level. These simple statements of complex problems have been rigorously formalised by Magnussen and Boudewyn (1998) and Magnussen et al. (1999).

6.2 Point estimates of canopy height

Before examining how stand or individual tree heights can be extracted from semi-random point patterns, we raise the issue of the accuracy of point estimates of canopy heights. In other words, what is the canopy height accuracy of a single lidar pulse return? This matter has, to our knowledge, never been studied empirically in the case of forest canopies.

The uncertainty of the planimetric position of single pulse returns renders field validation extremely difficult (Filin 2001). The other problem relates to the definition of a canopy surface, which, as discussed above, is an abstraction. Stating the problem in more theoretical terms, we ask the question, "what is the minimum amount of tree material (cumulative, one side projected, leaf and twig/branch surface) required so that a single incident pulse will generate sufficient returned energy to trigger a first return recording?" The corollary question is "how deep must a single pulse travel below an idealised canopy surface before a first return is recorded?" A number of key parameters that affect the analysis of this problem include: (i) laser energy and its distribution; (ii) first-return detection algorithms and appropriate critical thresholds; (iii) foliage density or LAI; (iv) foliage reflectance; and (v) incidence angle.

Concerning tree material density, Magnussen and Boudewyn (1998) report an approximate measure of "1 m^2 of needle surface (one-side projected) per 1 m^2 of crown surface and per 1 m^3 of crown volume" (p. 1018) for a 49 year old plantation of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). This strongly suggests that first returns have a Z position that is at least a little below the elevation of the first needles in the case of conifers. It also indicates that a pulse intersecting a conifer apex directly would probably yield a Z value below the apex. The implication is that mean canopy height estimates, based on average lidar heights, are probably biased to provide a lower height estimate, a fact that is not often recognised. Therefore, when estimating stand-wise Lorey's height from lidar heights issues to consider include: 1) that pulse returns usually fall on tree sides (not apices); and 2) that they penetrate the canopy surface to a certain extent.

6.3 Stand height

Practical methods for estimating stand height from lidar data resemble other remote sensing methods in that they require field calibration. Obviously, a height recovery model that could work with lidar data input alone would be ideal. Two such models were proposed and tested by Magnussen et al. (1999). Although results were encouraging, these models "hinge on a series of simplifying assumptions that naturally limit their application domain" (p. 415), i.e. they are applicable to idealised monospecific stands of trees with solid conical crowns. Empirical approaches based on simple heuristics have also been quite successful.

Window-based quantile estimators are clearly the most common approach for measuring stand height (Aldred and Bonnor 1985; Nilsson 1996; Næsset 1997; Magnussen and Boudewyn 1998; Næsset 2002). Although influenced by crown shape (tree species), stand density and stand structure (Nelson 1997), window-based quantile estimators can be designed to generate unbiased estimates of Lorey's height (Magnussen and Boudewyn 1998).

The method consists of determining a quantile of the lidar canopy height distribution that will reliably reflect average stand height. For kernals of various sizes operating on a lidar canopy height dataset, the lidar canopy height observation corresponding to the n^{th} quantile is taken as the local value of stand height. The stand-wise average of all kernel-extracted n^{th} quantile lidar observations is then computed. Both the precise quantile and the optimal kernel generally have to be identified through trial and error (Næsset 1997). Most studies report optimal window sizes around 20 m x 20 m and quantiles from 85 % to 95 %.

Calibration for such studies usually consists of measuring a few dozen stands for which 10-20 plots are sampled in the field. The lidar predictor is established on a stand basis, and not by comparing lidar windows to field plots. This approach is influenced by species and canopy structure, so calibration should incorporate the majority of stand types to produce a general-purpose estimator. This methodology is also known to be fairly robust with respect to lidar pulse return density. Positive results have been obtained with older lidar systems such as the ALTM1020, with canopy pulse return densities of 6-14 returns per 100 m^2 (Magnussen and Boudewyn 1998). This would allow measuring stand heights from low density, large area lidar surveys. Higher densities should, however, yield greater spatial precision and higher accuracies.

6.4 Individual tree height

Attempts to estimate individual tree heights for large areas may seem overly ambitious. However, Magnussen and Boudewyn (1998) demonstrate that the optimal quantile estimator is dependent on forest structure, the vertical distribution of LAI, and other variables for which accurate values are not normally available. This puts an upper limit on the accuracy of the grid-based methods for evaluating stand height. If the height of all trees emerging from the canopy could be estimated, then stand height estimation would be less influenced by forest structure. Furthermore, if the height of trees could be measured over a given area, significant insight could be gained into the structure of forest canopies, since height distributions and accurate stem maps (of visible trees) could be easily generated. This would undoubtedly open up new research possibilities in forest ecology. It could also replace, in some cases, field measurements of forest inventory plots or assist in calibration of lower density / wider coverage lidar surveys.

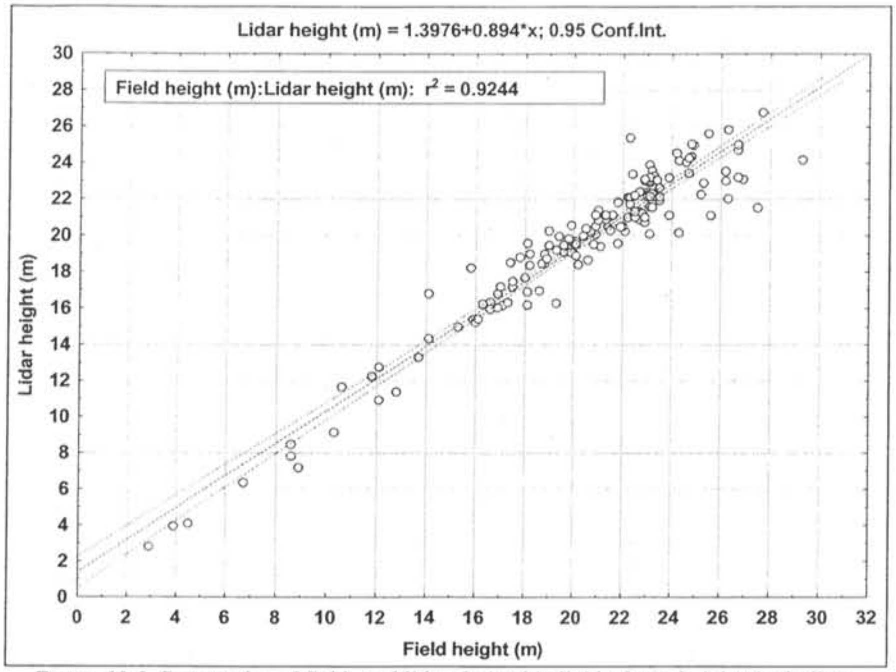


Figure 19-2. Scatter plot of field- and lidar-derived individual tree heights including regression line (reproduced with permission from Lim et al. 2001)

Individual tree height estimation is a relatively new area of research, as lidar systems that can provide sufficiently dense coverage have only recently entered the market. To our knowledge, only a few studies have addressed this issue (St-Onge 1999; Lim et al. 2001; Andersen et al. 2002; Persson et al. 2002). Results are encouraging, with typical field/lidar RMSE values approaching those of field-based measurements. In general, all attempts rely on identifying the highest lidar pulse in single crowns and comparing these values to the heights of the corresponding trees on the ground. As for stand height estimation, the fact that most pulse returns will be on the side of trees, and not on the apices, constitutes a problem. The probability of a pulse return falling close to a tree apex, however, increases at high pulse density. To alleviate this problem, field measurements are regressed against lidar estimations to produce a predictive equation (e.g. Figure 19-2). Coefficients of determination (r^2) for these are usually quite high (i.e. $r^2 >= 0.90$).

7. SUMMARY AND CONCLUSIONS

Tree and canopy heights are an important attribute for studies of forest structure and function. Height information may be used as an attribute or as an input to allometric equations for estimates of volume and biomass. Advances in GPS and inertial navigation systems now allow for accurate positioning of each lidar pulse return. High frequency lidar pulse rates now enable high pulse return densities while maintaining a relatively wide data swath. Improvements in lidar technology and processing techniques have combined to position lidar as a valuable tool for the monitoring of forest structure and function.

As presented in this Chapter, there is currently a reliable suite of techniques available, based largely upon quantile estimators, for estimating tree and canopy height. Improvements in lidar data processing methods are additive in nature. Future improvements may be made to lidar sensors and the raw data generated, to processing of the point cloud to determine ground and canopy models, to the creation of interpolated surfaces from the point data, and finally to the conversion of surfaces to grids. Improvements in these aspects will ultimately improve the height estimation of forest stands and individual trees. Techniques for the improvement of estimates of tree and canopy height will no doubt be an ongoing research endeavour.

REFERENCES

Aldred, A., & Bonner, M. (1985). Application of airborne lasers to forest surveys, *Information Report PI-X-51*, Canadian Forestry Service, Petawawa National Forestry Centre.

Andersen, H. -E., Reutebuch, S. E., & Schreuder, G. F. (2001). Automated individual tree measurement through morphological analysis of a lidar-based canopy surface model. *Proceedings of the First International Precision Forestry Symposium*, 11-22. June 17-20, 2001, Seattle, WA.

Axelsson, P. (2000). DEM generation from laser scanner data using TIN adaptive models. International Archives of Photogrammetry and Remote Sensing. *Proceedings of the International Society of Photogrammetry and Remote Sensing XIXth Congress*, B4, 110-117, Amsterdam, Netherlands.

Baltsavias, E. P. (1999). A comparison of between photogrammetry and laser scanning. ISPRS Journal of *Photogrammetry and Remote Sensing*, 54, 83-94.

Blair, J. B., Rabine, D., & Hofton, M. (1999). The Laser Vegetation Imaging Sensor (LVIS): a medium-altitude, digitization only, airborne laser altimeter for mapping vegetation and topography. *ISPRS Photogrammetry and Remote Sensing*, 54, 115-122.

Carabajal, C. C., & Harding, D. J. (2001). Evaluation of Geoscience Laser Altimeter System (GLAS) waveforms for vegetated landscapes using airborne laser altimeter scanning data. *Proceedings of the Land Surface Mapping and Characterization using Laser Altimetry, Joint Workshop of ISPRS III/3 and III/6*, 125-128. October 22-24, Annapolis, MD.

Dubayah, R., et al. (1997). The Vegetation Canopy Lidar Mission. *Land Satellite Information in the Next Decade II: Sources and Applications*, 100-112 American Society for Photogrammetry and Remote Sensing, Bethesda, MD.

Evans, D., S. Roberts, J. McCombs, & R. Harrington. (2001). Detection of regularly spaced targets in small-footprint lidar data: Research issues for consideration. *Photogrammetric Engineering and Remote Sensing*, 67, 1133-1136.

Filin, S. (2001). Recovery of systematic biases in laser altimeters using natural surfaces. *Proceedings of the Land Surface Mapping and Characterization using Laser Altimetry, Joint Workshop of ISPRS III/3 and III/6*, 85-91. October 22-24, Annapolis, MD.

Flood, M. (2001). Lidar activities and research priorities in the commercial sector. *Proceedings of the Land Surface Mapping and Characterization using Laser Altimetry, Joint Workshop of ISPRS III/3 and III/6*, 3-7. October 22-24, Annapolis, MD.

Harding, D. J., Lefsky, M. A., Parker, G. G., & Blair, J. B. (2001). Laser altimeter canopy height profiles: Methods and validation for closed-canopy, broadleaf forests. *Remote Sensing of Environment*, 76, 283-297.

Hese, S., & Lehman, F. (2000). Comparison of digital surface models of HRSC-A and LASER scanner for forest stand characteristics. International Archives of Photogrammetry and Remote Sensing. *Proceedings of the International Society of Photogrammetry and Remote Sensing XIXth Congress*, 33-Part B7/2, 525-532. Amsterdam, Netherlands.

Hill, J. M., Graham, L. A., & Henry, R. (2000). Wide-area topographic mapping and applications using airborne light detection and ranging (LIDAR) technology. *Photogrammetric Engineering and Remote Sensing*, 66, 908-914.

Hyyppä, J., Hyyppä, H., Inkinen, M., Engdahl, M., Linko, S., & Yi-Hong, Z. (2000). Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. *Forest Ecology and Management*, 128, 109-120.

Kraus, K., & 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.

Lefsky, M. A., Cohen, W. B., Acker, S. A., Parker, G. G., Spies, T. A., & Harding, D. (1999). Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forests. *Remote Sensing of Environment*, 70, 339-361.

Lefsky, M., Cohen, W., & Spies. T. (2001). 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, 78-117.

Lim, K., Treitz, P., Groot, A., & St-Onge, B. (2001). Estimation of individual tree heights using LIDAR remote sensing. *Proceedings of the Twenty-Third Annual Canadian Symposium on Remote Sensing*, Quebec, QC, August 20-24, 2001 (CD-ROM).

Lim, K., Treitz, P., Wulder, M., St-Onge, B., & Flood, M. (2002). LiDAR remote sensing of forest structure. *Progress in Physical Geography*, in press.

Luthcke, S., & Rowlands, D. (2001). Spaceborne laser altimeter instrument parameter calibration from integrated residual analysis. *Proceedings of the Land Surface Mapping and Characterization using Laser Altimetry, Joint Workshop of ISPRS III/3 and III/6*, 81-83. October 22-24, Annapolis, MD.

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

Magnussen, S., & Boudewyn, P. (1998). Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators. *Canadian Journal of Forest Research*, 28, 1016-1031.

Magnussen, S., Eggermont, P., & LaRiccia, V. N. (1999). Recovering tree heights from airborne laser scanner data. *Forest Science*, 45, 407-422.

Means, J. E., Acker, S. A., Harding, D. J., Blair, D. B., Lefsky, M. A., Cohen, W. B., Harmon, M. E., & 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.

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.

Nelson, R., Krabill, W., & Maclean, G. (1984). Determining forest canopy characteristics using airborne laser data. *Remote Sensing of Environment*, 15, 201-212.

Nilsson, M. (1996). Estimation of tree heights and stand volume using an airborne lidar system. *Remote Sensing of Environment*, 56, 1-7.

Ni-Meister, W., Jupp, D. L. B., & Dubayah, R. (2001). Modeling lidar waveforms in heterogeneous and discrete canopies. *IEEE Transactions on Geoscience and Remote Sensing*, 39, 1943-1958.

Nelson, R., Swift, R., & Krabill, W. (1988). Using airborne lasers to estimate forest canopy and stand characteristics. *Journal of Forestry*, 86, 31-38.

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.

Næsset, E. (2002). Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. *Remote Sensing of Environment*, 80, 88-99.

Optech (2001). *ALTM 2033 Brochure*, Optech Inc., Ontario, Canada.

Persson, Å., Holmgren, J., & Söderman, U. (2002). Detecting and measuring individual trees using an airborne laser scanner. *Photogrammetric Engineering and Remote Sensing*, in press.

Pfeifer, N., Reiter, T., Briese, C., & Rieger, W. (1999). Interpolation of high quality ground models from laser scanner data in forested areas. *ISPRS Workshop on "Mapping surface structure and topography by airborne and spaceborne lasers", Commission III, Working Group 3*, 31-36. La Jolla, Calif., 9-11 Nov. 1999.

Schreier, H., Lougheed, J., Tucker, C., & Leckie, D. (1985). Automated measurements of terrain reflection and height variations using an airborne infrared laser system. *International Journal of Remote Sensing*, 6, 101-113.

Solodukin, V. I., Kulyasov, A. G., Utenkov, B. I., et al. (1977). S' emka profilya krony dereva s pomoshch'yu laszer-nogo dal'nomera (Drawing the crown profile of a tree with the aid of a laser). *Lesn. Khoz*, 2, 71-73.

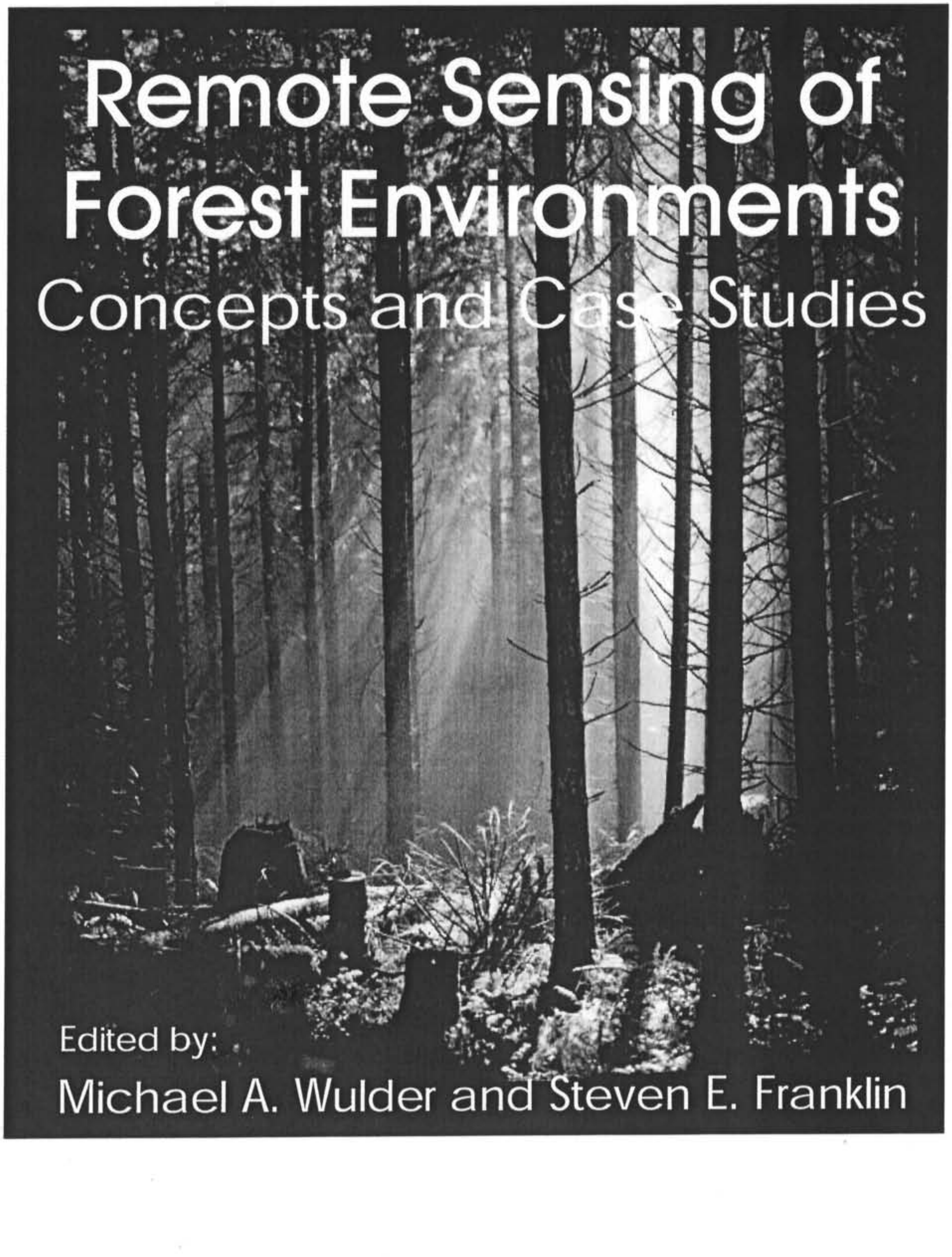
Spurr, S. H., & Barnes, B. V. (1980). *Forest Ecology*, (3rd ed.). Krieger Publishing Company, Florida.

St-Onge, B. (1999). Estimating individual tree heights of the boreal forest using airborne laser altimetry and digital videography. *ISPRS Workshop on "Mapping surface structure and topography by airborne and spaceborne lasers", Commission III, Working Group 3*, 179-184. La Jolla, Calif. 9-11 Nov. 1999.

St-Onge, B., & Renaud A. (2001). Estimating merchantable timber volume of aspen and spruce stands of the boreal forest using airborne laser altimetry. *Proceedings of the Twenty-Third Annual Canadian Symposium on Remote Sensing*, Quebec, QC, August 20-24, 2001 (CD-ROM).

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

Wulder, M. (1998). Optical remote sensing techniques for the assessment of forest inventory and biophysical parameters. *Progress in Physical Geography*, 22, 449-476.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