# Chapter 1
# Introduction to Forestry Applications of Airborne Laser Scanning

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**Abstract** Airborne laser scanning (ALS) has emerged as one of the most promising remote sensing technologies to provide data for research and operational applications in a wide range of disciplines related to management of forest ecosystems. This chapter starts with a brief historical overview of the early forest-related research on airborne Light Detection and Ranging which was first mentioned in the literature in the mid-1960s. The early applications of ALS in the mid-1990s are also reviewed. The two fundamental approaches to use of ALS in forestry applications are presented – the area-based approach and the single-tree approach. Many of the remaining chapters rest upon this basic description of these two approaches. Finally, a brief introduction to the broad range of forestry applications of ALS is given and references are provided to individual chapters that treat the different topics in more depth. Most chapters include detailed reviews of previous research and the state-of-the-art in the various topic areas. Thus, this book provides a unique collection of in-depth reviews and overviews of the research and application of ALS in a broad range of forest-related disciplines.

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## 1.1 Introduction

Satisfying national and international environmental goals and agreements requires heavy reliance on environmental mapping and monitoring. However, collection of information on the location and extent for many of the relevant characteristics of forest ecosystems by means of pure ground-based field inventories is prohibitively expensive. During the last decade, operational collection of such information has been revolutionized by the development of *Light Detection and Ranging* (LiDAR) – a technology producing distance measurements based on the return time of emitted light. LiDAR systems mounted on aircraft can be a cost-efficient means to obtain data on forest structure for vast geographical areas with high spatial resolution and high positional accuracy. The term *airborne laser* is frequently used to distinguish between systems that acquire LiDAR data from aircraft and systems using space-borne or terrestrial platforms. Most commercial airborne lasers, particularly those used for operational purposes, are equipped with a scanning device that distributes the emitted light across a wide corridor along the aircraft's flight path. Acquiring LiDAR data with these systems is known as *airborne laser scanning* (ALS).

A particular strength of ALS for forestry applications is its ability to accurately characterize the three-dimensional (3D) structure of the forest canopy. Such information is potentially more useful for forest inventories than the information from other remote sensing techniques (cf. Lefsky et al. 2001; Coops et al. 2004; Maltamo et al. 2006a). Height and density metrics derived from ALS data can be used to estimate the horizontal and vertical distribution of biological material for various forest growing stock and commercial timber surveys as well as ecological applications.

Research on the use of LiDAR data for forestry applications began in the mid-1970s with experiments using simple profiling instruments. Since approximately 1990, the emphasis has been development of tools for practical forest inventories that exploit the capability of ALS instruments to provide full areal coverage. ALS is currently incorporated as an essential component of operational forest inventories in multiple countries (Næsset 2007; Maltamo et al. 2011b; Woods et al. 2011). In addition, many countries and states are currently acquiring ALS data to construct detailed ground elevation models which then serve as a new data source for vegetation mapping and forest inventories (Nord-Larsen and Riis-Nielsen 2010). Nowadays, ALS data may be obtained for applications in a variety of fields from large numbers of providers and surveying companies, each with multiple systems.

Thus, ALS is recognized as a well-established and maturing discipline of both scientific and practical importance. Multiple scientific review articles (e.g. Lim et al. 2003; Næsset et al. 2004; Maltamo et al. 2007; Hyyppä et al. 2008; Koch 2010; McRoberts et al. 2010) and text book chapters (Koch et al. 2008; Packalén et al. 2008; Hyyppä et al. 2009) on ALS have been published in recent years. However, no full text book with a detailed overview on forestry applications is available. The aim of the present book is to fill this gap.

The overall purpose of this first chapter is to introduce and provide background for the subsequent chapters. Section 1.2 documents the early development of LiDAR for forestry applications with emphasis on ALS as that technology became available in the 1990s. Section 1.3 continues with a technological overview and description of basic techniques for using ALS data. The various applications described in Sect. 1.4 mainly refer to subsequent chapters. Finally, a brief overview of the structure of the book is presented.

## 1.2 Early Research on Application of Profiling LiDAR and ALS in Forestry

This section aims at documenting a few milestones important for the current development of ALS for forestry applications. The details are intentionally left to earlier reviews such as those by Lim et al. (2003) and Næsset et al. (2004) that reflect North American and Nordic perspectives, respectively. Nelson (2013) provides a comprehensive and historically interesting review on the early technical development from the mid-1970s to circa 1990.

The first studies on modeling forest attributes using ALS data continued previous research using data from airborne profiling LiDARs which, in turn, continued even earlier research using aerial photography. Nelson (2013) notes that the first mention of possible forestry applications was by Rempel and Parker (1964) who used an airborne profiling LiDAR system to obtain ground and tree heights. The first experiments to actually measure trees were reported by Solodukhin et al. (1976), who compared laser profiles of felled trees with tape measurements, later mounting the same instrument on an aircraft to acquire airborne profiles (Solodukhin et al. 1979). Similar studies using laser profilers were later conducted in North America (Nelson et al. 1984; Aldred and Bonner 1985; Maclean and Krabill 1986), and some studies developed methods for estimating forest volume and biomass from the airborne canopy profiles (Maclean and Martin 1984; Maclean and Krabill 1986).

Arp et al. (1982) also used a profiling system, along with aerial photography, to map forest height in Venezuela. The earliest uses of LiDAR data to support forest inventories were extensions of similar uses of photogrammetric data. Maclean and Martin (1984) reported $0.75 \leq R^2 \leq 0.87$ for a regression model of the relationship between timber volume and cross-sectional areas of canopy profiles obtained from aerial photography. The early LiDAR studies mimicked this approach using data from profiling LiDAR systems acquired for a narrow transect along the aircraft flight line. Aldred and Bonner (1985) used LiDAR profile data to estimate stand heights within 4.1 m of actual stand heights and to assign stands to crown density classes with 62 % accuracy. Maclean and Krabill (1986) obtained $R^2 \approx 0.9$ for a regression model of the relationship between gross merchantable volume and cross-sectional areas derived from laser profiles. Nelson et al. (1984) used data from a profiling system to characterize vertical forest canopy profiles. Means of LiDAR-based and photography-based estimates of tree heights along flight lines were comparable and linear models of the relationship between photo-interpreted canopy closure and LiDAR metrics produced $R^2 \approx 0.8$. Schreier et al. (1985) demonstrated the utility of LiDAR profiling data for distinguishing among coniferous trees, deciduous trees, and low-growing vegetation. Nelson et al. (1988) constructed linear models of relationships between height, mean volume per unit area, and mean biomass per unit area as response variables and height profile metrics derived from LiDAR profiling data as predictor variables and obtained $0.50 \leq R^2 \leq 0.60$. For forest inventory purposes, the important lesson learned from these early LiDAR profiling studies was that regression models using LiDAR metrics could be used to predict forest attributes of interest. The successors to LiDAR profiling systems were ALS systems with both small footprint diameters in the range 0.1–2.0 m and large footprint diameters in the range 5.0–10.0 m. Data from ALS systems are better suited than profiling data when full coverage is necessary.

An important step towards the commercial development of LiDAR measurements was the integration of Global Positioning System (GPS) and Inertial Navigation Systems (INS) in the 1990s which facilitated accurate positioning of the scanner and, consequently, the recorded data. Using some of the first commercial or pre-commercial systems equipped with GPS and INS (Næsset et al. 2004), multiple researchers reported relevant relationships between field-measured and ALS-based height metrics, typically quantified in terms of mean height (Nilsson 1996; Næsset 1997a; Magnussen and Boudewyn 1998; Magnussen et al. 1999). Further, simple stand level mean or total values of forest biophysical variables such as basal area (Means et al. 2000) and stand volume (Næsset 1997b; Means et al. 2000) were estimated from small-footprint ALS data with similar or better accuracies than those produced by pure sample-based ground methods.

The first studies focused on relationships between plot-level forest attributes based on field measurements and ALS-based height distributions. These approaches are characterized as *area-based* and are distinguished from *individual tree* approaches proposed a few years later by Brandtberg (1999) and Hyyppä and Inkinen (1999) that focused on detecting individual trees from surface models constructed using ALS data. Both area-based and individual tree approaches have been tested for ALS-based forest inventories, and variants and hybrid methods have also been developed (Sect. 1.3.2).

## 1.3 Technical Basics

### *1.3.1 General Principles of ALS*

Overviews of theoretical and physical aspects of ALS that were published in the late 1990s (Baltsavias 1999; Wehr and Lohr 1999) still constitute useful sources of information. The physical principles of ALS are also described in Chap. 2 of this book. The basis of all ALS systems is emission of a short-duration pulse of laser light and measurement of the elapsed time between emission and detection of the reflected light back at the sensor. Using the speed of light, the elapsed time is converted to the distance from the point of emission to the underlying object from which the light was reflected. Because the position and the orientation of the sensor are recorded using a GPS and INS, ALS data constitute a set of 3D coordinates that represent the scanned surface from which the pulses were reflected.

ALS instruments used in forestry applications are typically small-footprint, discrete-return systems that record from one to a few echoes for each emitted pulse. The diameter of the emitted laser beam on the ground, characterized as the beam's footprint, depends on the beam divergence and the flying altitude. Small footprint proprietary systems typically have footprint diameters of 1 m or less and are often preferred for forestry applications because they facilitate accurate linkages between the scanning data and individual trees, plots, or forest stands. In contrast, large footprint systems typically have footprint diameters as great as 10s of meters. The spacing of pulses on the ground depends on parameters such as flying altitude and speed, pulse repetition frequency, viewing angle, and scanning pattern.

The emitted laser pulses generate different types of data as they are reflected from the ground and recorded at the sensor, depending on the interaction with the forest canopy (cf. Chap. 2) and whether the sensor has full-waveform capabilities or is a discrete return system. In simplified terms, full-waveform recording systems (Chap. 3) digitize the entire sequence of returned energy as a function of height, whereas most systems described in the following chapters are discrete return systems that record from one to a few (typically four to five) discrete echoes reflected from between the bare earth and the top of the canopy. The recorded data of discrete return systems depend on factors such as the algorithm used in real time to trigger and record echoes from the backscatter signal received at the sensor. Depending on the sensor, additional information for properties such as the intensities of echoes may be recorded.

## *1.3.2 Basic Inventory Techniques*

### 1.3.2.1 Area-Based Approaches

A fundamental concept underlying the area-based approach is that the 3D point cloud consisting of the heights corresponding to all the echoes for a given surface area, for example a sample plot, contains information that can be used to characterize the ground surface and the vertical distribution of the biological material in the vegetation layers above that area. For most applications, the vertical ALS height distribution for a particular area ignores the horizontal position of individual echoes within the area in question but maintains heights for all echoes. The entire ALS height distribution, or the portion of it representing the vegetation, can then be used to calculate discrete metrics that are related to properties of the distribution of biological material. Metrics include parameters of the ALS height distribution such as the mean or percentiles and parameters related to the canopy density such as penetration rates. The ALS height distribution can also be approximated by continuous distribution functions.

Magnussen and Boudewyn (1998) showed that the proportion of small footprint ALS echo heights at or above a given reference height corresponded well with the proportion of leaf area above this height. Although leaf area is generally not an inventory variable of interest, a seminal contribution of this study was demonstration of the utility of ALS height percentiles as predictor variables. This innovative approach has subsequently been found useful for prediction of a wide range of forest attributes. Several extensions of this concept are relevant. First, ALS pulse densities for spatial units used for model calibration should be sufficiently large to produce reliable estimates of the parameters of the echo height distributions used as model predictor variables. Second, pulse densities should be sufficiently large to estimate these parameters for both spatial units used to calibrate models and spatial units used for areal estimation. The latter feature permits calibration of models using ground and ALS data for circular plots and estimation using square grid cells of the same area.

As noted by Magnussen and Boudewyn (1998), the number of pulses per spatial unit must produce reliable estimates of ALS metrics used to predict forest attributes. In this regard, minimum pulse densities have rarely been less than 0.1 pulses/m$^2$ (Næsset 1997b; Holmgren 2004), and minimum plot areas have rarely been less than 200 m$^2$ (Næsset 2002; Andersen and Breidenbach 2007; Gobakken and Næsset 2008; Breidenbach et al. 2008; Maltamo et al. 2011a, b). Although multiple reports of the effects of varying pulse densities on ALS-based volume and biomass estimates have been published, the results are not directly comparable because common plot areas were not used; similarly, reports of the effects of varying plot sizes are not directly comparable because common pulse densities were not used. However, when the results of these comparative studies are expressed in terms of pulses per plot, Thomas et al. (2006), Maltamo et al. (2006b), Breidenbach et al. (2008), and Gobakken and Næsset (2008) all reported that reducing pulse densities to 100–225 pulses per plot had no adverse effects on the quality of fit of volume or biomass models when using echo height deciles as predictor variables. Holmgren (2004), Magnusson et al. (2007), and Strunk et al. (2012) all reported that reducing the number of pulses per plot to 50 or fewer had no serious adverse effects on model fits or estimates. Thomas et al. (2006) compared not only qualities of fit but also the distributions of echo heights for pulse densities of 200 and 2,000 pulses per plot, and reported that the distributions were essentially the same.

Næsset (1997a) compared means of stand-level heights for 36 stands using tree measurements for approximately 15 plots per stand to three ALS-based means: arithmetic mean ALS height, mean weighted ALS height, and the within-stand mean over 15 × 15 m cells of the greatest ALS height per cell. The latter means deviated the least from the means based on tree measurements. Næsset (1997b) estimated stand volume from multiple linear and nonlinear models using three small footprint

ALS metrics as independent variables: mean stand height calculated as the mean of maximum echo heights for small grid cells, mean height of all ALS echoes, and canopy cover density calculated as the proportion of canopy echoes. $R^2$ values ranged from 0.45 to 0.89, depending on the site. A seminal contribution of these two studies was the idea of tessellating a spatial study area into grid cells, predicting the response variable for each grid cell, and calculating the mean over grid cells as an estimate for the entire study area (see further details in Chap. 11).

The insight of Magnussen and Boudewyn (1998) regarding the necessity of a sufficient number of pulses to characterize the vertical distributions of ALS echo heights, in combination with the grid cell approach proposed by Næsset (1997a, b), led Næsset and Bjerknes (2001) to select grid cells with the same areas as plots used to calibrate prediction models. Næsset (2004) provided a partial rationale for selecting spatial units of equal areas and a caution against using ALS metrics such as maximum height that depend on plot size. However, Zhao et al. (2009) proposed models using ALS metrics based on echo height distributions that can be calibrated using spatial units of one size and applied to spatial units of different sizes. Magnussen et al. (2013) proposed the use of cumulants (moments) of distributions of ALS canopy heights to predict plot-level distribution of forest attributes such as tree diameter, basal area, and volume. Despite these advances, the issue of whether models constructed using plots with particular areas and pulse densities can be applied without adverse effects to grid cells with different areas and pulse densities, particularly in a readily implementable and efficient manner, remains somewhat uncertain.

Numerous investigations of procedures for characterizing relationships between forest attributes and ALS metrics have been reported of which only those making unique contributions are cited herein. In a university-industry partnership, Means et al. (2000) used linear models and commercially available small footprint ALS data to predict height, basal area, and volume. Packalén and Maltamo (2006), Hudak et al. (2008), Latifi et al. (2010), and Andersen et al. (2011) investigated non-parametric approaches including nearest neighbors imputation. Maltamo et al. (2004), Breidenbach et al. (2008), and Vauhkonen et al. (2011) investigated linear mixed effects models with random stand-level intercepts, and Breidenbach and Kublin (2009) and Junttila et al. (2008) investigated Bayesian methods.

Lefsky et al. (2002), Næsset et al. (2005), Jensen et al. (2006), Næsset (2007), Breidenbach et al. (2008), and Asner et al. (2012) investigated using common models for relationships between forest attributes and LiDAR metrics for differing forest conditions. For response variables such as volume, biomass, and carbon, the prospects for common models were positive under the condition that the sensor systems and acquisition parameters were stable across study areas (Næsset 2009). However, for a comprehensive dataset consisting of 1,395 plot-level observations representing 10 different boreal forest areas, Næsset and Gobakken (2008) reported that the quality of fit of models to aboveground biomass data was significantly improved by including variables related to proportions spruce and proportion broadleaf trees (see also Chap. 11).

#### 1.3.2.2 Individual Tree Approaches

For tree-level inventories, ALS data are typically used to detect individual treetops and to predict attributes of interest using sets of allometric models. Algorithms and techniques similar to those developed for aerial images can be used with ALS data (Hyyppä et al. 2008). Tree-level inventories consist of a sequence of steps that includes tree detection, feature extraction, and estimation of tree attributes. For these applications, the ALS data contributions include estimation of heights of the vegetation surface; estimation of physical properties such as height differences between potential tree tops during tree detection; estimation of individual tree heights and crown sizes used as input to the allometric models (e.g. Hyyppä and Inkinen 1999; Persson et al. 2002); and avoidance of problems related to variations in geometry and radiometry of spectral images (e.g. Mäkinen et al. 2006).

Detection of individual trees usually relies on a raster-based canopy height model (CHM) interpolated from the ALS height data (e.g. Hyyppä and Inkinen 1999; Persson et al. 2002; Popescu et al. 2003), although point-based techniques could be used, particularly for the segmentation (see Chap. 5). An important consideration is that all trees cannot usually be detected. The degree to which individual trees are successfully detected is affected by the detection algorithm and its parameterization (Kaartinen et al. 2012). In addition, detection success is strongly affected by forest conditions, particularly stand density and spatial pattern, which suggest problems related to both interlaced tree crowns and trees below the dominant canopy (Vauhkonen et al. 2012a). Methods for resolving these problems include selection of an appropriate level of filtering a priori (Heinzel et al. 2011; Ene et al. 2012), use of full-waveform data (Reitberger et al. 2009) and improved 3D algorithms (Lähivaara et al. 2014; Tang et al. 2013).

The estimation task requires that relevant information for estimating tree attributes of interest must be extracted from the ALS data. Tree-level estimation combines direct measurements, species-specific properties that can be predicted from the ALS data, and tree allometry in the form of dimensional relationships between plant parts. In addition to estimates of locations, the tree detection and delineation component typically produces heights, crown dimensions, and height and intensity distributions for individual tree segments (e.g. Holmgren and Persson 2004). Estimates for the latter properties are particularly useful for ALS-based species recognition (Chap. 7).

Use of allometric models to estimate attributes such as the diameter at-breast-height (DBH) poses problems, because relationships between measurable tree dimensions and DBH are far from deterministic but rather are affected by factors such as tree density and silvicultural history (Korpela 2004; Maltamo et al. 2007). Geometrically weighted regression methods have been investigated as a means of overcoming at least some of these problems (Salas et al. 2010). Propagation of errors in the ALS-based DBH estimates to stem taper model predictions can be avoided by estimating stem volumes directly from the ALS data using regression models (e.g. Takahashi et al. 2005) or nearest-neighbor techniques (e.g. Maltamo et al. 2009), which can use a large number of predictor variables (Vauhkonen et al. 2010).

Multiple tree-level studies have focused on individual tree detection, feature extraction, and estimation steps in this inventory procedure. Remarkably, however, few studies have reported plot- or stand-level estimates obtained from the full detection and estimation procedure (Korpela et al. 2007; Peuhkurinen et al. 2007, 2011; Vauhkonen et al. 2014). The accuracy of aggregated estimates depends on multiple factors including both tree-level detection and tree-level estimation errors. Undetected trees and errors in the allometric model predictions degrade the accuracies of plot- and stand-level estimates and seriously constrain single-tree applications in semi-natural forests (Korpela et al. 2007). Approaches that attempt to circumvent the effects of these error sources such as semi-individual tree detection are being developed (Breidenbach et al. 2010, Chap. 6). The individual tree approach may be most relevant for applications such as wood procurement planning for which unbiased estimators are not necessarily required (e.g. Peuhkurinen et al. 2007; Vauhkonen et al. 2014).

Finally, the complementary properties of the individual tree and area-based approaches should be noted. In addition to actual tree detection, data on individual trees can be generated by predicting diameter distributions with the area-based approach (Chap. 9), while combining these approaches has been found especially beneficial for reducing tree detection errors (Maltamo et al. 2004; Breidenbach et al. 2010; Lindberg et al. 2010). Breidenbach et al. (2012) and Vastaranta et al. (2012) proposed generating field reference data for the area-based approach by means of modified tree detection approaches. Vauhkonen et al. (2014) used an area-based mean diameter prediction for targeting detailed tree-level analyses for stands that are sufficiently mature for cutting. In addition to the earlier mentioned height distribution, other feature types can also be calculated at area and tree levels (e.g. Hyyppä et al. 2012; Vauhkonen et al. 2012b; Ørka et al. 2013), and for some applications, the addressed domain may even be difficult to identify (e.g. Vauhkonen et al. 2011; Mehtätalo and Nyblom 2012, Chap. 10).

## 1.4 Applications

The first studies of forestry applications of ALS focused on traditional forest inventory variables such as height, basal area and volume (e.g. Næsset 1997a, b; Hyyppä and Inkinen 1999; Means et al. 2000). The context for these studies was usually stand level management inventories using the area-based approach. Rather soon thereafter operational use of ALS for this purpose was initiated in Norway (Chap. 11) and subsequently in other countries. These first inventories were complemented by economic analyses of the costs and benefits of the use of ALS as an auxiliary source of information (Chap. 16). In Finland, because estimates of species-specific stand attributes are required, ALS data were combined with aerial image data (Chap. 12). Issues related to the co-registration of the different sources of data are discussed in Chap. 4. Nowadays, area-based forest inventories are increasingly conducted for different forest conditions such as plantations

(Chap. 13). Since circa 2008, use of ALS as a sampling mechanism has rapidly become more common (Chap. 14), especially for larger regional studies for which full ALS coverage obviously is cost prohibitive. Multiple ALS-assisted sampling approaches can still produce estimates with high precision. Thus, the currently most relevant forest inventory applications are for National Forest Inventories and tropical REDD + inventories. Additional ALS-assisted inventory applications include pre-harvest (e.g. Vauhkonen et al. 2014) and conservation inventories (Chaps. 17, 18, and 19).

The ability of ALS data to characterize the 3D structure of forest canopies facilitates numerous ecological applications. Some ecological parameters such as canopy cover (Chap. 20) and canopy gaps (Chap. 21) can be almost directly estimated from ALS data. While a highly accurate estimate for canopy cover can be calculated as a proportion of vegetation hits above a specified height limit, canopy gaps can be detected from a CHM. Measures associated with these variables are among the most obvious attributes that can be simply estimated from ALS data. Estimation of some other traditional forest inventory variables, such as biomass and volume, using ALS data can be based on allometric relationships, but may require considerably more complex, multi-step procedures (see Chap. 8).

Vertical forest structure, another key ecological parameter, can also be estimated from ALS data. Such information is useful and interesting if for no other reason than to distinguish canopy layers. However, this information can also be used as input to fire risk (Chap. 22) and habitat models (Chap. 17). To date, most ALS-assisted habitat models are for bird species (e.g. Hill et al. 2004), although recent studies have also focused on mammals (Melin et al. 2013). ALS has become an important information source for species level biodiversity studies (Chap. 18) that focus on characteristics such as richness, diversity, composition (e.g. Müller and Brandl 2009), and naturalness (e.g. Bater et al. 2009). Finally ALS data have been used to model deadwood attributes (Chap. 19) and to guide field inventories of deadwood (e.g. Pesonen et al. 2010).

## 1.5 Structure of the Book

ALS has gained widespread acceptance as an important and useful source of auxiliary information for describing the 3D structure of forests. Researchers and practitioners alike have found these data useful for forest inventory, ecological and environmental research. The overall intent of the book is to provide a comprehensive, state-of-the-art review for these areas of application. The book is organized into three parts following this introduction. Because inventory, ecological and environmental disciplines share the same basic approach to extraction of information from the primary data, Part I (Chaps. 2, 3, 4, 5, 6, 7, 8, 9, and 10) focuses on methodological issues. However, most of the book is devoted to applications which are further organized into two parts. Part II (Chaps. 11, 12, 13, 14, 15, and 16) focuses on forest inventory applications at multiple geographical scales, from local, operational, wall-to-wall management inventories to regional, strategic, sampling-based inventories, and Part III (Chaps. 17, 18, 19, 20, 21, and 22) focuses on ecological and environmental applications. The application chapters of Parts II and III refer back to the general treatment of methodological issues in Part I whenever appropriate; thus, cross-references among chapters are frequent.

Because most chapters are written as state-of-the-art reviews, the book can be viewed as a comprehensive and unique review of a wide range of forestry applications of ALS. Many of the chapters focus on boreal forests simply because methods were initially developed for boreal conditions. The reviews provide a sufficiently comprehensive overview of recent research and applications that researchers, students and practitioners should all find the book to be a useful reference text.

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