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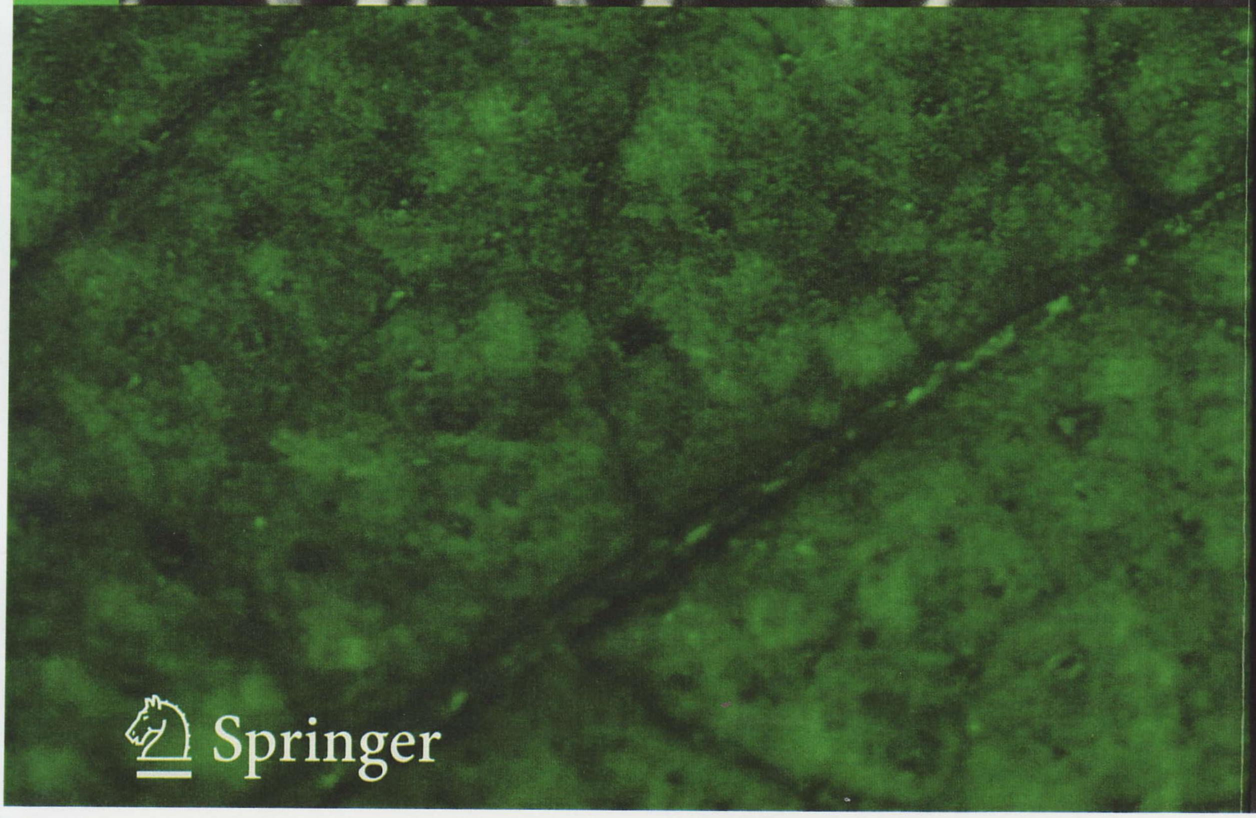
Plant Responses to Air Pollution and Global Change



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3-D remote sensing of woody canopy height and carbon stocks by helicopter-borne scanning lidar

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Summary. A method for 3-D remote sensing of forest canopies using high-resolution, helicopter-borne scanning lidar is presented. The lidar device can scan almost all the ground surface with high resolution because a laser beam with a small footprint and a high scanning rate illuminates the ground surface from a slow-moving helicopter. The method permits the generation of 3-D images such as a Digital Elevation Model, Digital Terrain Model, and Digital Canopy Height Model (DCHM). The validity of the method was demonstrated in two applications. First, we estimated tree height from a DCHM of a forest on a steep slope, and found that errors were within 0.47 m for tree height (0.19 m RMSE). These results show that the estimation of tree height was greatly improved compared with estimates in previous studies. Second, we estimated carbon stocks in each tree and in the stand as a whole. From lidar-derived tree heights and allometric relationships between tree height and carbon stocks, we accurately estimated total carbon stocks of each tree in a coniferous Japanese cedar (*Cryptomeria japonica*) forest as well as carbon stocks at the stand scale.

Key words. 3-D remote sensing, Woody carbon stock, DEM, DTM, DCHM, Helicopter-borne scanning lidar, Tree height

1. Introduction

Accurate estimation of canopy structures and biomass in forests is crucial for studying the functioning of forests and in studies of the global carbon budget. Remote-sensing techniques have been proven to be reliable tools for assessing environmental changes and their impacts on forests in recent decades. Satellite-based sensors, such as Landsat TM and NOAA AVHRR, can observe wide areas efficiently and have been shown to be effective in many ecological applications (Waring et al. 1995; Goward and Williams 1997). However, these conventional sensors have significant limitations for forestry applications because their sensitivity and accuracy have repeatedly been shown to decrease as aboveground biomass increases (Waring et al. 1995; Turner et al. 1999). In addition, they cannot fully represent the 3-D spatial features of forests.

Lidar (light detection and ranging, a laser-based equivalent to radar) has become a popular, active remote-sensing technology, and its applications to 3-D terrestrial observation have been developing rapidly. Lidar offers many advantages in forestry compared

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with the abovementioned conventional sensors; in particular, it allows measurement of the 3-D distribution of forest canopies. Since the mid-1980s, non-scanning airborne lidar has been used to estimate the average height of forest trees and forest biomass (Nelson at al. 1988). In the mid-1990s, scanning lidar became available, and this technology was soon applied for forest measurement (Nilsson 1996; Næsset 1997; Means et al. 1999). However, ordinary scanning lidar systems with small-footprint lasers were unable to illuminate the entire ground surface because of the high flight speed of the aircraft and the device's low pulse frequency (Flood and Gutelius 1997; Næsset and Økland 2002). As a result, tree tops are not captured exactly by using this system, and tree heights are underestimated. Another airplane-based lidar system, which uses large-footprint lidar with a large scan width, has been used for remote sensing of forests on a regional scale (Nilsson 1996; Means et al. 1999; Harding et al. 2001). The large footprint lidar can cover large areas and fully illuminate the ground surface. However, its spatial resolution is restricted because of its large footprint.

Recently, spatial resolution has been improved by the use of scanning lidar with a small footprint and a high pulse frequency, mounted on a helicopter, which can travel at slower speeds than airplanes can (Omasa et al. 2000, 2003; Brandtberg et al. 2003; Maltamo et al. 2004). These systems are expected to more completely illuminate the ground surface and generate more accurate 3-D data, thereby enhancing the usefulness of scanning lidar. Work using conventional lidar systems has focused on measuring forest attributes such as the mean tree height. However, recent systems based on lidar with high spatial resolution can measure individual trees rather than estimating average values for the stand (Brandtberg et al. 2003). In this paper, remote sensing of forests using a high-resolution, helicopter-borne scanning lidar is presented to reveal the technique's potential.

2. Measurement of the forest canopy

Fig. 1 shows a schematic diagram of the helicopter-borne scanning lidar system that we used (Omasa et al. 2000). The elapsed time between the emitted and returned laser pulses was measured, and was used to calculate the distance to the object returning the signal. This system offers two receiving modes: a first-pulse mode (FP-mode) and a last-pulse mode (LP-mode). Laser pulses returned from the outermost canopy surface and from the ground surface were received simultaneously in FP-mode and LP-mode, respectively. In the experiment, more LP-mode beams reached the ground surface through forest canopies because the setting of the footprint for the LP-mode beam was smaller than that of the FP-mode beam. Because of the helicopter's low flight speed (50 km h^{-1}) and the lidar's high pulse frequency (25 kHz), each footprint interval nearly equaled the footprint diameter (about 30 cm), and as a result, almost the entire ground surface could be illuminated.

We determined the 3-D geographic position of each data point using a helicopter-borne internal measurement unit (IMU) combined with global positioning system (GPS) devices in the helicopter and on the ground. We generated a Digital Elevation Model (DEM) with a highly precise grid (10×10 cm) by interpolating the lidar data. The canopy surface was described by a DEM created from the FP-mode data, and the ground surface was described as a Digital Terrain Model (DTM) by interpolating the LP-mode data for the ground surface. We then produced a Digital Canopy Height Model (DCHM), which

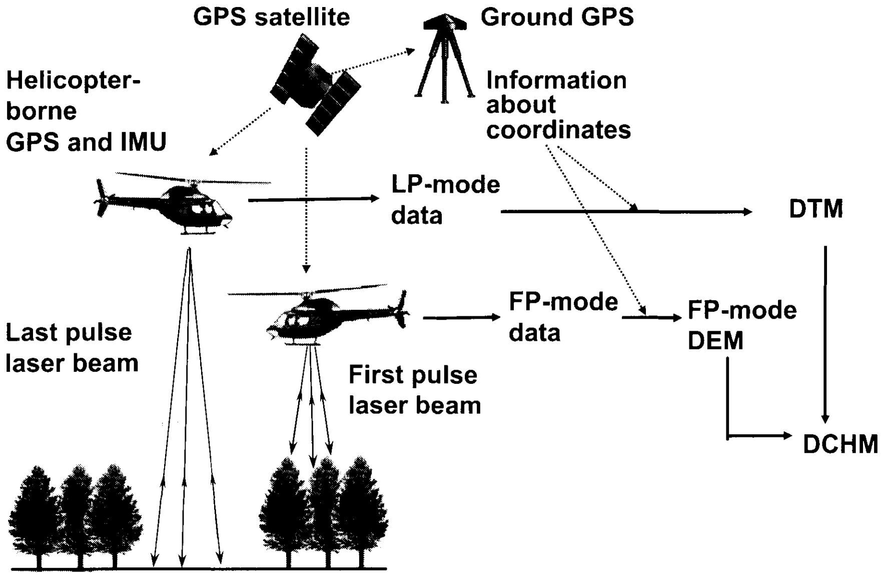

Fig. 1. A schematic diagram of the 3-D remote-sensing system based on helicopter-borne scanning lidar.

shows the net tree height after accounting for variations in ground elevation, by subtracting the LP-mode DTM values from the FP-mode DEM values.

3. Estimation of ground surface and woody canopy heights

We tested our system at a site located at the foot of a mountain (in Shizuoka, Japan), where the ground surface slopes steeply (Omasa et al. 2000). Fig. 2A shows a 3-D view of the resulting FP-mode DEM. All trees, buildings, and roads can be clearly distinguished. This image shows that our method effectively generates a precise 3-D image of the forest's woody canopy. The elevation of each point in this image is still influenced by the slope of the ground, so tree height cannot be estimated directly from this image; only differences in canopy height can be estimated. In contrast, Fig. 2B shows the DTM produced from the LP-mode data. The ground surface obstructed by the presence of trees was interpolated relative to adjacent ground points measured using the LP-mode. The slope and undulations of the ground can be clearly recognized in this image. Map data and ground-truth measurements confirmed that the DTM was accurate despite of the presence of many trees. Fig. 2C shows the DCHM used to estimate canopy height at the study site after correction for the influence of the ground slope and undulation (i.e., by subtracting the DTM data from the corresponding DEM data). We estimated the errors in the lidar data by comparing the lidar-derived data with the ground-truthed data. The results showed an error within 0.47 m in tree height (0.19 m RMSE; Table 1).

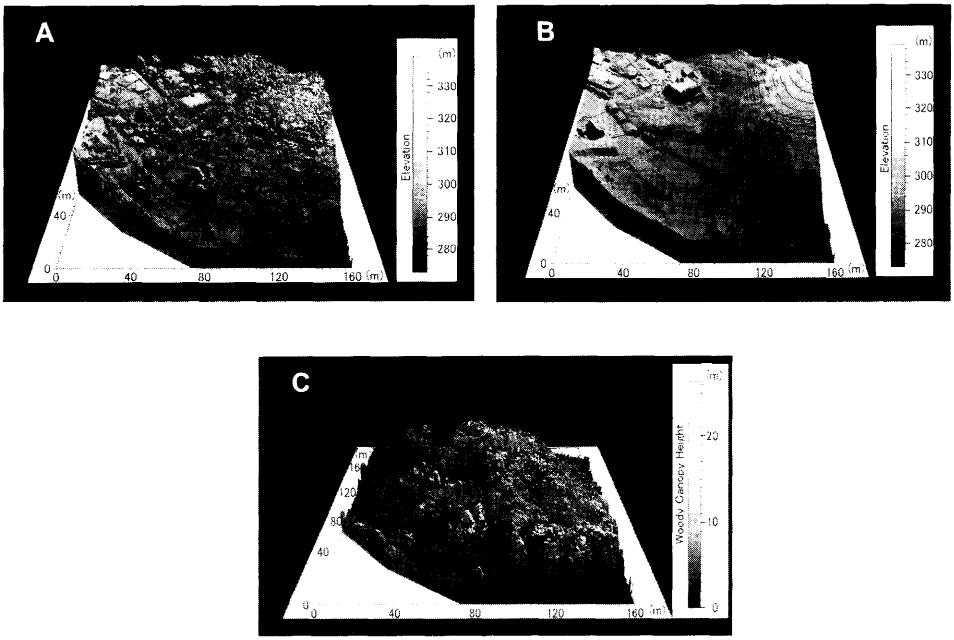

Fig. 2. 3-D views of the study site: (A) the DEM created from the FP-mode data; (B) the DTM created from the LP-mode data; (C) the DCHM created by correcting the DEM using the DTM data (Omasa et al. 2000).

Table 1. Measurements of the height of the forest canopy.

Tree species	Ground-truthed tree heights		Error in the lidar data	
	Range (m)	Mean (m)	Range (m)	RMSE (m)
Coniferous trees	11.20 to 19.65	15.05	-0.47 to 0.19	0.19
Broadleaved trees	1.95 to 10.40	6.58	-0.40 to 0.13	0.12

4. Estimation of the forest's carbon stock

Accurate estimation of the carbon stocks of forests is crucial for understanding the global carbon budget and climate change. The height data for a forest canopy obtained from helicopter-borne lidar can be used to accurately estimate forest carbon stocks. For example, Omasa et al. (2003) and Patenaude et al. (2004) successfully used small-footprint lidar to estimate forest carbon stocks. In our study (Omasa et al. 2003), the carbon stocks of each tree in a coniferous Japanese cedar (*Cryptomeria japonica*) forest were estimated by using allometric relationships between lidar-derived tree heights and the corresponding carbon stocks.

We generated the DCHM by subtracting the DTM created from the LP-mode values from the DEM created from the FP-mode values as shown in Fig. 3. Each tree height at the site was automatically determined from the DCHM image by means of filtering to identify the highest point in the canopy surface for each tree. Fig. 4 shows the resulting image for the highest point of trees in the DCHM image. The trees in this image are all Japanese cedars. The position of the highest point of a given tree corresponds with the position of its stem. Therefore, Fig. 4 identifies the position of each tree stem. The error in tree height ranged from –0.25 to –0.42 m, with an RMSE of 0.38 m, compared with the ground-truthed data. Fig. 5 shows the tree height distribution of the study site obtained from the DCHM. Tree heights range from 6.0 to 27.0 m, with an average height of 21.3 m, and most heights (90%) range between 18.5 and 26.0 m.

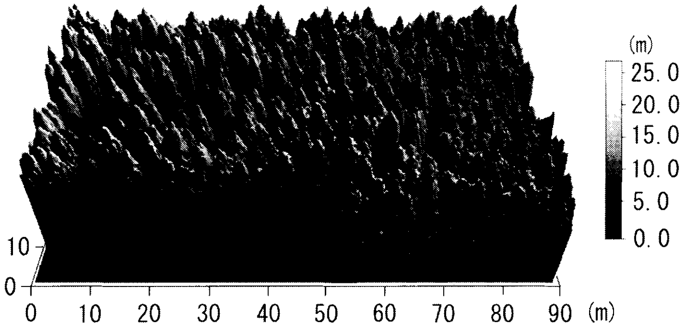

Fig. 3. A 3-D view of the DCHM for the Japanese cedar forest (Omasa et al. 2003).

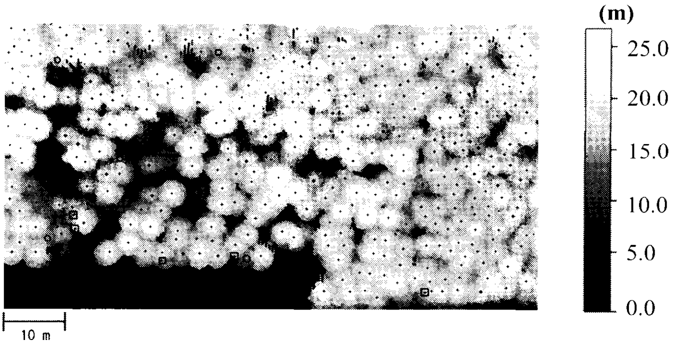

Fig. 4. The highest point of each tree in the DCHM image (Omasa et al. 2003).

We developed a regression equation for estimating the stem carbon stocks from tree height, using both field data for our study site and all other available data on Japanese cedar in Japan (212 datasets) (Cannell 1982). We estimated the carbon stocks of a tree stem (C_{stem}, kg C tree^{-1}) as follows:

$$C_{\text{stem}} = 0.0119H^{2.9696}\ (r^2 = 0.933)$$

where H is tree height (m). We developed another regression equation for estimating the carbon stocks of branches, foliage, and roots from tree height using data collected all over Japan (53 datasets) (Cannell 1982). The carbon stocks of these parts (C_{BFR}, kg C tree^{-1}) were estimated as follows:

$$C_{\text{BFR}} = 0.0075H^{2.9516}\ (r^2 = 0.864).$$

Using these two equations, we obtained the spatial distribution of carbon stock for each tree at the study site shown in Fig. 6. The gray level inside each outline represents the

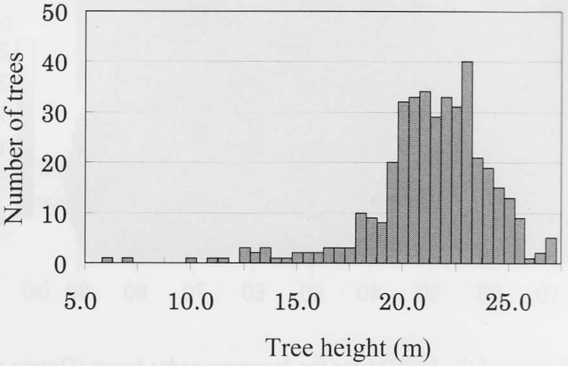

Fig. 5. The distribution of tree heights estimated from the DCHM data (Omasa et al. 2003).

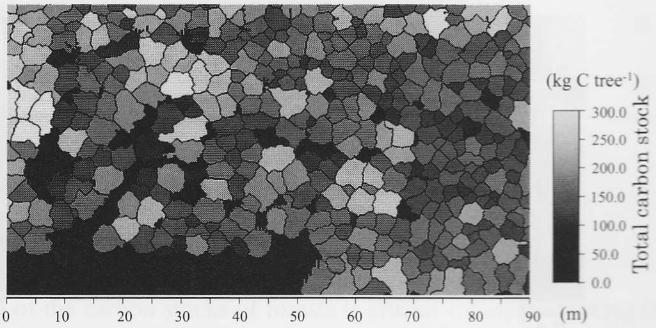

Fig. 6. Estimated carbon stock of each tree in the Japanese cedar forest (Omasa et al. 2003).

total carbon stock of that tree and covers the area occupied by that tree's canopy. The maximum carbon storage per tree was less than 300 kg, with most values between 110 and 300 kg. Total carbon storage at the site was estimated at 69 300 kg C, and the average carbon storage was estimated at 175.9 kg C tree^{-1}. The results reveal that 3-D remote sensing using helicopter-borne lidar accurately estimated carbon stocks at the stand scale.

5. Conclusions

In this paper, we demonstrated two applications of 3-D remote sensing using a high-resolution, helicopter-borne scanning lidar system. In the lidar system, a laser beam with a small footprint and a high pulse frequency illuminates the ground surface from a slow-flying helicopter, and almost all of the ground surface can be scanned at high resolution. The lidar was proven to be effective for obtaining accurate measurements of canopy height and for creating a DTM. Using allometric relationships combined with lidar-derived data, we could also estimate carbon stocks both for individual trees and for the stand as a whole. The 3-D lidar remote-sensing technique thus represents additional progress in the use of remote sensing to accurately estimate various forest properties.

References

Brandtberg T, Warner TA, Landenberger RE, McGraw JB (2003) Detection and analysis of individual leaf-off tree crowns in small footprint, high sampling density lidar data from the eastern deciduous forest in North America. Remote Sens Environ 85:290–303

Cannell MGR (1982) World forest biomass and primary production data. Academic Press, London, 145-166

Flood M, Gutelius B (1997) Commercial implications of topographic terrain mapping using scanning airborne laser radar. Photogramm Eng Remote Sens 63:327–366

Goward SN, Williams DL (1997) Landsat and earth systems science: development of terrestrial monitoring. Photogramm Eng Remote Sens 63:887–900

Harding DJ, Lefsky MA, Parker GG, Blair JB (2001) Laser altimeter canopy height profiles: methods and validation for closed-canopy, broadleaf forests. Remote Sens Environ 76:283–297

Maltamo M, Eerikäinen K, Pitkänen J, Hyyppä J, Vehmas M (2004) Estimation of timber volume and stem density based on scanning laser altimetry and expected tree size distribution functions. Remote Sens Environ 90:319–330

Means JE, Acker SA, Harding DJ, Blair JB, Lefsky MA, Cohen WB, Harmon ME, McKee WA (1999) Use of large-footprint scanning airborne lidar to estimate forest stand characteristics in the Western Cascades of Oregon. Remote Sens Environ 67:298–308

Næsset E (1997) Determination of mean tree height of forest stands using airborne laser scanner data. ISPRS J Photogramm Remote Sens 52:49–56

Næsset E, Økland T (2002) Estimating tree height and tree crown properties using airborne scanning laser in a boreal nature reserve. Remote Sens Environ 79:105–115

Nelson R, Krabill W, Tonelli J (1988) Estimating forest biomass and volume using airborne laser data. Remote Sens Environ 24:247–267

Nilsson M (1996) Estimation of tree heights and stand volume using an airborne lidar system. Remote Sens Environ 56:1–7

Omasa K, Akiyama Y, Ishigami Y, Yoshimi K (2000) 3-D remote sensing of woody canopy heights using a scanning helicopter-borne lidar system with high spatial resolution. J Remote Sens Soc Jpn 20:394-406

Omasa K, Qiu GY, Watanuki K, Yoshimi K, Akiyama Y (2003) Accurate estimation of forest carbon stocks by 3-D remote sensing of individual trees. Environ Sci Technol 37:1198–1201

Patenaude G, Hill RA, Milne R, Gaveau DLA, Briggs BBJ, Dawson TP (2004) Quantifying forest above ground carbon content using LiDAR remote sensing. Remote Sens Environ 93:368-380

Turner DP, Cohen WB, Kennedy RE, Fassnacht KS, Briggs JM (1999) Relationships between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. Remote Sens Environ 70:52–68

Waring RH, Way J, Hunt ER Jr, Morrissey L, Ranson KJ, Weishampel JF, Oren R, Franklin SE (1995) Imaging radar for ecosystem studies. Bioscience 45:715-723