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METHODOLOGICAL INSIGHTS

A portable LIDAR system for rapid determination of forest canopy structure

GEOFFREY G. PARKER*, DAVID J. HARDING† and MICHELLE L. BERGER*

**Smithsonian Environmental Research Center, 647 Contee's Wharf Road, Edgewater, MD 21037, USA; and †NASA Goddard Space Flight Center, Geodynamics Branch, Mail Code 921, Greenbelt, MD 20771, USA*

Summary

1. The functional characteristics of forests are related to the organization of their canopies. However, understanding the relationship between canopy structure and function has been limited by a paucity of methods for determining structure at scales consistent with those of function measurements.

2. We describe here a portable system, assembled from commercially available components, for acquiring measurements of distances to overhead plant surfaces. These measurements can be aggregated to assess canopy structure rapidly at scales of ecological interest. Deployed from the forest floor, the system includes a narrow-beam rapidly pulsed first-return laser rangefinder coupled with a data recording system.

3. Tests in an age sequence of broad-leaved closed-canopy forests showed that the system provides results significantly more rapidly than previous methods, at spatial scales as small as 1 m in all dimensions. The estimated mean vertical canopy structure is consistent with that found from more laborious, manual approaches, such as the foliage height profile method. The system has some biases due to beam width and range averaging but, from a variety of tests, we found these have relatively little effect on the structure estimates.

4. Various field sampling schemes and methods of aggregating the measurements yield a variety of representations of structure, including mean profiles, tomographic sections, three-dimensional distributions of canopy surface density and maximum height surfaces. Derivable summary measures include canopy cover and area index, porosity, the size distribution of overhead openings and indices of structural complexity. Moreover, the approach can provide estimates of spatial variability and covariance not previously obtainable.

5. *Synthesis and applications.* Portable light detection and ranging (LIDAR) systems, such as the one we describe here, provide a new tool for rapid measurement of small-scale forest structure. These can contribute efficiently and relatively inexpensively to canopy research and forestry programmes, covering a range of ecological and production needs.

Key-words: canopy height profile, complexity, laser rangefinder, metrics, spatial variation, visualization

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Introduction

The canopy, the aggregate of all crowns in a stand of vegetation, is critically important for a variety of processes. The canopy houses the machinery of photosynthesis and controls growth and production, affects microclimates at various scales, and provides habitat for a diversity of organisms. The structure of the canopy is an important influence on, and indicator of, all these functions. Aspects of structure can indicate the stand developmental stage and potential for growth, the diversity of included habitats, and may predict stand attributes important in stand management, such as stem density, basal area and above-ground biomass.

Common measurements of canopy structure are simple spatial summaries, such as the fraction of ground overlayed by foliage (coverage), the maximum stem height and the leaf area per unit ground area (leaf area index, LAI). Such summaries are often inadequate for predictions of growth, carbon dioxide exchange,

Correspondence: Geoffrey G. Parker, Smithsonian Environmental Research Center, 647 Contee's Wharf Road, Edgewater, MD 21037, USA (fax +443 482 2380; e-mail parkerg@si.edu).

structural complexity and habitat quality; structural information on the spatial distribution of canopy components is more useful than summary measures (Parker 1995; Lefsky *et al*. 2002).

MANUAL METHODS

In the common ground-based method for characterizing the vertical distribution of foliage (optical point quadrats, OPQ), an observer determines, at many locations in the stand, the height to the nearest leaf overhead. This is done by manually focusing an upward-viewing telephoto lens calibrated to measure distance (MacArthur & Horn 1969). The resulting distribution of intercepted distances is adjusted for the effect of the occlusion of far targets by near ones, to yield the relative vertical distribution of leaves, the foliage height profile (FHP). This adjustment, referred to as the MacArthur–Horn transformation (M-H), assumes that the probe is infinitely thin and that canopy elements are Poisson-randomly distributed in space. The transformation is sensitive to differences in canopy cover, so accurate estimation of cover is important (Radtke & Bolstad 2001). The OPQ method does not yield absolute LAI but it provides relative height profiles (Aber 1978; Hedman & Binkley 1988; Brown & Parker 1994) and has been validated in broad-leaved forests by Fukushima, Hiura & Tanabe (1998). Because this approach is very labour intensive it has only been used for plot- and stand-scale summaries.

Such summary measures describe mean conditions, providing no information on spatial variability. A similar but more qualitative method characterizes vertical structure by noting whether canopy material is present or absent at height intervals at many points (Karr & Roth 1971; Hubbell & Foster 1986; Terborgh & Petren 1991; Brockelman 1998; Brokaw & Lent 1998). When conducted at numerous locations, this method can provide a classification of forest structural environments (Connell, Lowman & Noble 1997; Bongers 2001).

LIDAR METHODS

The basis for detailed canopy structure information is a set of spatially referenced distance measurements. Light detection and ranging (LIDAR), which measures distance by time-of-flight using pulsed laser light (Bufton 1989), can provide these. Lefsky *et al*. (2002) distinguish two main types of LIDAR systems used in remote sensing of vegetation, waveform-recording and discrete-return. Waveform-recording systems measure the vertical distribution of intercepted canopy surfaces and the underlying ground surface within a single footprint using high-speed digitization of the backscattered return from a short-duration laser pulse (Harding *et al*. 2001). This technology has been employed experimentally from aeroplanes (Blair, Rabine & Hofton 1999; Harding *et al*. 2000) and NASA spacecraft (Garvin *et al*. 1998; Zwally *et al*. 2002). The diameter of the laser footprint is large for these airborne (5–25 m) and space-based (70–100 m) sensors.

Harding *et al*. (2001) showed that waveform-based vegetation height profiles retrieved from an airborne platform were similar, in several forests, to coincident OPQ height profiles obtained from the ground, when both were corrected for occlusion. However, because LIDAR systems do not easily distinguish leaves from other surfaces (Radtke & Bolstad 2001; Lefsky *et al*. 2002) the derived vertical profile is termed a canopy height profile (CHP), in contrast with the FHP described by MacArthur & Horn (1969). By analogy with terminology for foliar structure (Parker 1995), the height profile of the complete surface area is denoted C(h), and its sum over all heights is the canopy area index, CAI.

Discrete-return LIDAR systems measure the distances to one or a few surfaces in a small diameter spot from which the backscattered laser energy exceeds a detection threshold. They are most commonly employed in terrain mapping (Baltsavius 1999) but have also been used in research on vegetation canopies (Nelson, Krabill & Tonelli 1988; Ritchie *et al*. 1993; Parker & Russ 2004). Airborne LIDAR systems that record the range to the first and/or last intercepted surface have been utilized to determine the height of vegetation and the topography of the outer canopy surface (Nelson, Krabill & Tonelli 1988; Ritchie *et al*. 1993; Nilsson 1996; Magnussen, Eggermont & LaRiccia 1999; Naesset & Bjerknes 2001). However, the relatively large diameter laser beam, typically 0·5–1 m, in these studies means that, for closed canopies, the laser pulse is intercepted by vegetation at or near the outer canopy surface, with few observations on the internal organization of the canopy. Discrete-return LIDAR systems that distinguish multiple (as many as five) targets per laser pulse are now in use commercially. Although these have the potential to characterize better the distribution of surface area within the canopy, that capability has not yet been demonstrated. LIDAR systems with very closely spaced small footprints (e.g. 0·1 m), typically deployed on helicopters, can range through small gaps, yielding a distribution of first intercepts that more completely samples surface area throughout the canopy (Blair & Hofton 1999).

Several limitations hinder the utility of airborne and space-based LIDAR systems for investigations of canopy structure. For typical airborne systems, the costs for instrument deployment and data acquisition and processing are high, making studies of small areas impractical, and frequent, repeated measurements to observe temporal variations are prohibitively expensive. Data from the NASA satellite-based systems, while available at no cost, are limited in geographical and temporal coverage and of low spatial resolution.

A variety of ground-based LIDAR systems can acquire ranges for angles in two dimensions. For example, Vanderbilt (1985) studied the geometry of a row crop with a scanning system. Tanaka, Yamaguchi & Takeda (1998) reconstructed 3-dimensional forest geometries by triangulation using images of the planar trace of a visible laser beam intercepting canopy elements. However, such instruments are generally not portable and often have a limited range.

A portable system is needed for rapid and accurate measurement of canopy structure at ecologically significant scales. It should be readily assembled from commercially available components, straightforward in operating principle, and easy to use under a variety of field conditions. Our objectives were to describe and evaluate such a system, to demonstrate some numerical and graphical products, and illustrate its utility for studies of vegetation structure and processes that depend on that structure.

We chose not to design and build a waveform-recording system because this would not be easily assembled or widely available. Instead we investigated existing commercial systems that record discrete ranges using pulsed laser diodes. We identified desirable characteristics of the system, evaluated several available laser rangefinders, and selected one that best met the requirements. We evaluated this instrument in laboratory tests and then adapted it for field use by integrating it with a rugged carrying frame, power supply and data acquisition system. We tested the system in a variety of canopies and canopy situations to compare it with other methods and to understand its biases, repeatability and capacity to detect a variety of structures. We also developed approaches to reduce the data, measures useful for characterization and comparison, and some visualizations of the resulting volumetric data.

Methods and results

RANGEFINDER CHARACTERISTICS THAT AFFECT STRUCTURE ESTIMATES

Many rangefinders achieve high precision through signal processing that rejects low-quality reflections and then averages the acceptable distances. Averaging of multiple targets at different ranges can delete observations and result in a distance to a fictitious target. In some instruments, the number of ranges involved in averaging can depend on characteristics such as the quality of the reflected signal. The procedure for determining this can be proprietary and not apparent to the user.

The M-H method used to derive canopy height profiles from distributions of ranges assumes that the probe (represented here by the beam of laser light) is infinitely thin. Two characteristics of common rangefinders interfere with this assumption. First, most lasers are not coaxial (the locations of beam exit and reflectance capture can differ by as much as 15 cm), the implied parallax means that the capacity to penetrate an aperture involves the combined geometry of outgoing and reflected pulses. Secondly, the beam exiting the laser is often large and changes with distance in a way that depends on the optics of the system. Large beams are unlikely to range between closely spaced canopy elements and may be overly sensitive to near targets. This is especially problematic where aperture size is small relative to beam size. Beam diameter is in practice limited by the need for eye safety; laser energy sufficient to range successfully to 'uncooperative' foliage and woody targets high in the canopy requires a relatively broad beam (> 5 cm in typical commercial rangefinders) in order to avoid ocular damage. The actual diameter of probes and laser beams was found to have a large effect on estimates of LAI in grass swards (Warren Wilson 1963) and in row crops (Denison 1997).

Given the above limitations, critical rangefinder characteristics for measurements of canopy structure are: (i) a rapid and regular pulse repetition rate (> 10 Hz, preferably 1 kHz); (ii) portability; (iii) accuracy of < 0·1 m; (iv) unambiguous reporting of 'sky hits', where no plant area is intercepted; (v) ability to measure targets from very close to the instrument to a maximum height of forests (100 m); (vi) eye safety; (vii) continuous data capture; and (viii) commercial availability. Other desirable features include: (i) control over averaging of distance measurement; (ii) a narrow beam divergence; (iii) a small beam diameter; and (iv) a uniform distribution of laser energy within the beam.

We tested the Disto Memo and Disto Classic models (Leica Geosystems Inc., Norcross, GA), the Ledha/Geo (Jenoptik Laserdiode GmbH, Jena, Germany), the Impulse LR 200 (Laser Technology Inc., Englewood, CO), the Red Dot Visible laser and the Pulseranger 76-0380 (Cubic Precision, Teterboro, NJ) and the LD90-3100HS and LD90-3300VHS-FLP (Riegl Laser Measurement Systems, Horn, Austria). All systems are discrete-return rangefinders, measuring the distance to the closest detected surface. All are sufficiently accurate but they vary regarding other requirements. Most have a low pulse rate or are not eye safe. The Disto models, and to some extent the Impulse LR 200, have a small beam size but often do not return a range measurement under canopy conditions. The Riegl LD90-3300VHS-FLP is high speed and unaveraged but is not eye safe and has a very large beam size with a segmented, non-uniform energy distribution at distances greater than 20 m. The Riegl LD90-3100HS meets most requirements best: it is an eye safe, laser safety class I (ANSI 1993) first-return type rangefinder operating at 890 nm and 1 kHz. However, it has two problematic characteristics: a relatively large exit beam and unavoidable averaging of ranges. At a minimum, the Riegl LD90-3100HS laser averages five ranges together to give one measurement. If five consecutive laser pulses do not return, the system waits for as many as 10 pulses to obtain five acceptable returns before giving a 'no-return' error message.

LABORATORY TESTS ON THE RIEGL LD90-3100HS

Beam size

We traced the shape and measured the dimensions of the laser spot at a variety of distances (1, 2, 5, 10, 20 and

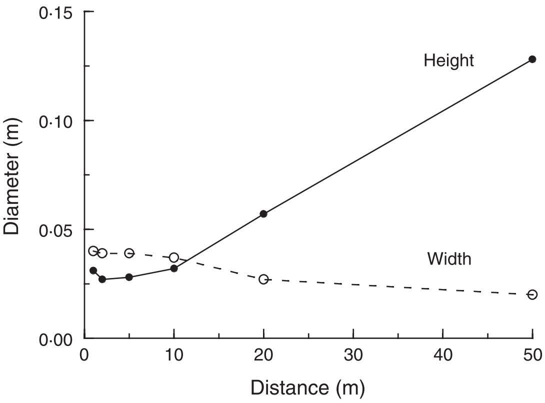

Fig. 1. Change in the shape (height and width) of the Riegl LD90-3100HS laser beam with distance.

50 m) by observing the beam on a flat target with an infrared-sensitive camcorder (Sony Handycam Steady Shot XR, Sony Corp., Tokyo, Japan). The rectangular emergent beam was 12·4 cm^2 but increased to only 25·6 cm^2 at 50 m, consistent with the manufacturer's specification of an angular divergence of 2·0 mrad (Fig. 1). The beam shape changed from horizontally elongated at close distances to vertically exaggerated at long distances (Fig. 1).

Target sensitivity

We quantified the rangefinder's response to foliage of differing reflectivity, shape and orientation. We also measured its ability to detect targets of various sizes and to range through narrow apertures. All of the following tests were conducted with the laser averaging five ranges.

The laser detected a variety of foliage targets (shiny and dull laminar leaves, short and long coniferous needles) equally well (within the 3–4 cm typical error reported by the manufacturer) at close (2 m) and intermediate (20 m) distance. Laminar leaves that were rotated showed no significant change in accuracy until the leaf was almost parallel to the beam. At angles more than 70° from perpendicular the averaged range measurement was biased long by pulses reflected by the wall behind the target leaf. Needle-leaved foliage, short or long, was similarly ranged at all angles and at both distances. However, the measured distance was not to the leading needle but to a location several centimetres within the clump.

We used wooden dowels of nine diameters (from 1/8 to 1 inch; 3·4–25·4 mm) to test the sensitivity of the rangefinder to obstacle size. These targets were positioned 2·0 m in front of a flat wall and at various distances (1, 2, 5, 10, 20 and 50 m) from the laser. Replicate measurements ($n = 5$) were made and measurements were scaled by the distance between the target and wall as an index of relative error: [(measured distance – actual distance to target)/2 m]. Low values indicated high sensitivity (only the target was seen) while high values indicated low sensitivity (the wall behind the target was predominantly ranged).

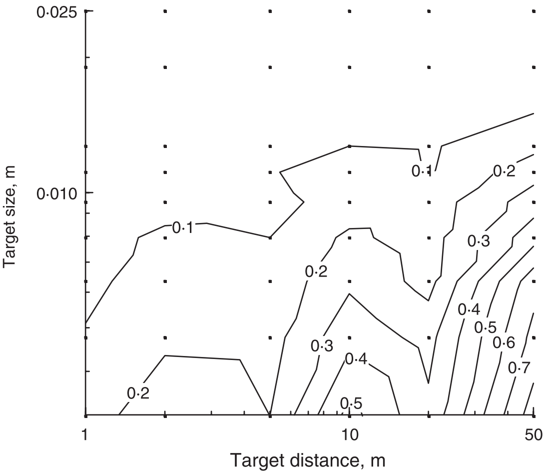

Fig. 2. Relative ranging error for cylindrical targets of various diameters placed at various distances away from the Riegl LD90-3100HS, presented as a contour graph. Small values indicate that targets were reliably acquired. Filled squares indicate variable combinations where measurements were taken.

Relative error increased with both increasing target distance and smaller target size, i.e. as the angular size of the target decreased (Fig. 2). The more accurately measured targets were near ones, especially those with diameters greater than 0·01 m.

To assess the system's capacity to range through apertures we constructed a flat target with a square, adjustable opening. This was positioned 2·0 m in front of a wall at various distances (1, 2, 5, 10, 20 and 50 m) from the laser. Apertures were varied (2, 3, 4, 5, 6, 7, 8, 10, 15, 20, 25, 30 and 35 cm diagonally) and replicate measurements ($n = 5$) were made. Measurements were scaled by the distance between the target and the wall as an index of relative error: [(actual distance to wall – measured distance)/2 m]. Low values indicated aperture penetration (the wall beyond was ranged) while high values indicated the beam was blocked.

These results showed that the system was unable to penetrate through some apertures to range reliably the wall beyond (Fig. 3). The opening size at which the beam was always blocked was about 2 cm at close range, increasing to 4 cm at long distances. However, it could reliably see through holes of 6 cm (when close) to 10 cm (when far away).

Range averaging

The effect of averaging on a distance measurement depends not only on the number of values averaged but also on the rate at which new targets are encountered. Together these conditions influence the chance that all distances grouped are not from the same target. The first effect is controlled in data processing (either within the instrument or in later analysis) and the second effect depends on how the instrument is moved with respect to multiple targets. To test these effects we employed another, high-speed (2 kHz), rangefinder to gather unaveraged range information on a 300-m transect along a

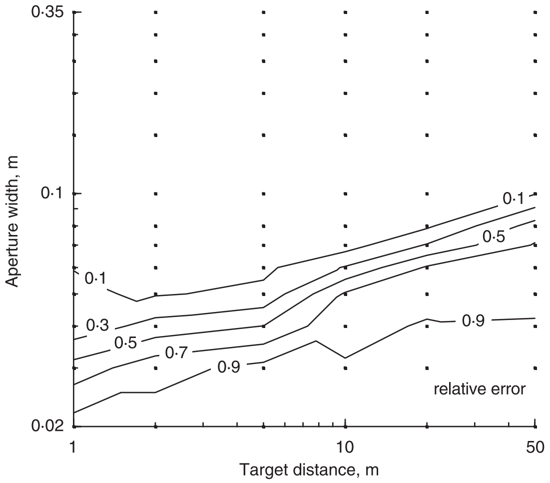

Fig. 3. Relative ranging error for a target with a variable sized opening placed at various distances away from the Riegl LD90-3100HS, presented as a contour graph. Small values indicate the opening was penetrated by the system while large values indicate blockage. Filled squares indicate variable combinations where measurements were taken.

wooded road. This rangefinder, a Riegl LD90-3300VHS-FLP, while appropriate for the purpose of the test, has too large a beam and is not eye safe for regular use in the system we describe. To vary the rate of new target appearance we moved the rangefinder at two speeds, once walking (1·2 m s^{-1}, giving 1688 ranges m^{-1}) and again from a slow-moving truck (3·6 m s^{-1}, 550 ranges m^{-1}). We grouped the raw data in progressively larger sets (doubling, from 2 to 2048), averaged these, and compared each resulting distribution of distances to the original unaveraged distribution. As a measure of deviation from the base case, we calculated the mean difference across heights of the fraction of all observations.

Averaging had little effect on the distance distributions until the measurement groups were around 64 (walking) and 32 (driving), where the lines in Fig. 4 begin to rise. Note that the 5-range averaging at 1000 Hz (equivalent to 10 at 2000 Hz) routinely utilized by the Riegl LD90-3100HS system (arrowed in Fig. 4) falls in the flat portion of the curves.

MODIFICATION FOR FIELD USE

We connected the rangefinder to a lightweight laptop computer with data-logging software and constructed a rugged and stable platform that could be carried comfortably (Fig. 5). To keep the system level and decouple its movement from the operator's motion, we first used a gimballed platform, modified from one used for steadying a movie camera. However, we found that in many situations the low-hanging counterweight struck forest floor obstacles, causing even more motion than without it. Ultimately we constructed a flat platform and found it could be carried sufficiently level without gimballing. Early versions were made of angle-iron, but later ones were fabricated of stainless steel, with a shape designed to minimize projections that might be caught on obstacles.

The complete system weighed 11·2 kg and could be carried comfortably for at least an hour. The platform measured 0·83 × 0·33 m and was attached to a person with an adjustable hip belt and shoulder straps. Although it could not be used during precipitation or when the understorey was extremely wet, we found it useful in a wide variety of environments (cold and hot, dry and humid) and very rugged overall. The laser required 12-Volt DC power and 1 amp of current, readily supplied for many hours of field use with a small motorcycle battery. The rangefinder, at about US $8000 (as of 2003), was the largest component of the total cost of about $12 000. This total could be reduced with a different data acquisition system and platform. Most small computers capable of acquiring serial data at 19 600 bits s^{-1} will suffice. Typical data file sizes are about 50 kB min^{-1} sampling, consisting of an ASCII string of range measurements and an optional amplitude value.

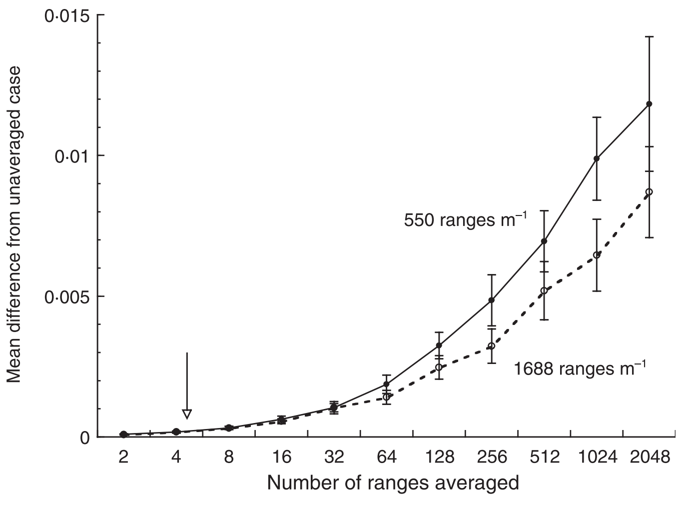

Fig. 4. Differences from unaveraged distance distribution as ranges are averaged in progressively larger groups (2–2048 measurements) in cases where velocity during sampling was slow (open symbols) or more rapid (filled).

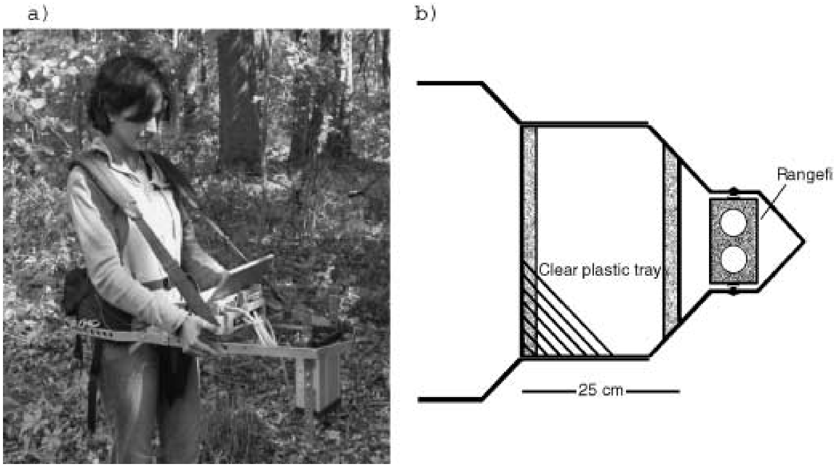

Fig. 5. The canopy laser rangefinder in use on the forest floor (a) and a schematic plan diagram of the walking platform (b).

OTHER SENSORS

To identify ranges taken when the system was not level, we used a two-axis inclinometer (model CXTILT02-E; Crossbow Technology, San Jose, CA). However, as will be discussed later, this was not found useful for routine integration in the field system. A global positioning system (GPS) could also be incorporated for acquiring absolute locations (Nelson, Parker & Horn 2002); however, obtaining accurate GPS positions under forest canopies is difficult (Hulbert & French 2001), especially when moving.

STANDARD FIELD DEPLOYMENT

When the rangefinder was attached to the frame and laptop computer, distance measurements to canopy surfaces overhead could be collected by walking a transect at a constant rate. The reference plane of the rangefinder was kept as level as possible at 1 m above the ground. The laser lens was covered before and after sampling; the resulting small ranges were easily identified at the beginning and end of the data file.

DATA ANALYSIS

Raw data files were edited to retain only ranges obtained while sampling and to identify laser pulses where no vegetation target was detected, assumed to be 'sky hits.' For the Riegl LD90-3100HS this condition was indicated by an error code for no range. Estimating the plant area density for a section of canopy required several steps. First, we grouped the ranges in horizontal bins. In our experience, a distance of 2 m is a compromise between acquiring some sky observations and enough samples to characterize the overhead surface distribution. Secondly, we formed the frequency distribution of ranges by 1-m tall bins and estimated the cover. From these we calculated the relative CHP, using the M-H transformation. Note these values sum to unity over all heights in the column. This process was repeated for each horizontal bin along a transect.

A contiguous series of relative CHP is not particularly informative because columns with high canopy density are not distinguishable from adjacent low-density columns. To provide a consistent basis for comparison, we estimated the total canopy area in each column using a procedure suggested by MacArthur & Horn (1969) and further developed by Parker & Tibbs 2004). The relation between leaf cover and LAI was obtained from a series of simultaneous observations of both measures during autumn abscission in the forest test plots. The negative exponential equation relating leaf cover to LAI had an exponential constant averaging 0·5. We used this relation to estimate total canopy surface area in a column (CAI) from total cover. This approximation, the 'overlap transformation', is intended to facilitate comparison across columns.

FIELD STUDY AREAS

To validate the system in the field, several plots were established in four stands of very different vertical structure. All stands were within 1 km of each other on similar soils, at and in the vicinity of the Smithsonian Environmental Research Center (SERC), about 10 km south-south-east of Annapolis, Maryland, USA (38°53′N, 76°33′W). Each was a separate stage of the 'tulip poplar' association (Brush, Lenk & Smith 1980; Eyre 1980), a mixed deciduous forest type with overstorey often characterized by *Liriodendron tulipifera*. There was a young stand with a compressed monomodal canopy, a stand of intermediate age with an expanded monomodal canopy, a mature stand with a bimodal leaf area distribution and an old-growth area with a more even vertical leaf area structure. Each plot was 30 × 30 m. Summary information on the stands is given in Table 1. The intermediate, mature and old-growth stands were studied in Brown & Parker (1994) and are referred to in their appendix table as kph4, twrc and frg1 and frg2, respectively. This series is representative of major structural changes during development in this forest type. This pattern includes a rapid equilibration of LAI, litterfall

Table 1. Ecological characteristics of the intensive forest study plots at the Smithsonian Environmental Research Center (SERC) in 2001. Density, basal area and above-ground biomass were estimated from all live stems at least 2·0 cm in d.b.h. Litterfall is from the autumn collection. LAI was derived from litterfall using species-specific equations for estimating foliage area from the dry weight of leaf samples

	Stem density (ha^{-1})	Basal area (m^2 ha^{-1})	Biomass (Mg ha^{-1})	Litterfall (Mg ha^{-1})	LAI (m^2 m^{-2})
Young	4711	23·8	86·2	3·72	5·58
Intermediate	1022	32·1	198·0	3·80	5·33
Mature	1156	38·7	285·8	4·19	6·35
Old-growth	867	36·3	292·2	3·96	5·86

and basal area, with a progressive increase in biomass and stem thinning.

Stem sampling

In each stand we identified the species and measured the diameter at breast height (d.b.h) of every stem 2·0 cm or larger within the plot. Above-ground stem biomass was estimated from d.b.h. using the general relation of White (1985).

Leaf area index

Leaves were retrieved approximately weekly from litter collectors ($n = 9$) in each plot throughout the autumn abscission period. Leaves were sorted by species, dried to 60 °C and weighed. Species leaf area was obtained from dried leaf mass using species-specific equations (Parker, O'Neill & Higman 1989). Leaf areas were summed across species to yield total leaf area collected. LAI was estimated as the total leaf area collected divided by the total collector aperture.

Canopy structure measurements

In each of the four plots, 31 parallel 30-m transects separated by 1 m were walked with the Riegl LD90-3100HS laser system. We also sampled the same 31 transects with another laser, the LTI Impulse LR 200. This laser does not provide continuous ranges, so it was manually triggered approximately every metre along the transect at 1 m above the ground. OPQ measurements of canopy structure were also collected using a calibrated 200-mm telephoto lens. At 25 stations evenly distributed in each of the 30 × 30-m plots, the distance to surfaces above 15 grid intersections was measured. The camera lens was level at 1 m above the ground. The measurements with both lasers and the OPQ method were collected within days of each other in each plot during the summer of 2001.

FIELD EVALUATION AND VALIDATION

Profiles

We compared the distributions of distance measurements derived from the OPQ method, the manually triggered LTI Impulse laser and the Riegl system in each forest plot. The total number of distances measured in each plot varied greatly among methods, from 375 for the OPQ approach, to about 1100 for the LTI rangefinder, to more than 340 000 for the Riegl instrument. All three measurement methods yielded similar range distributions (Fig. 6). The profiles from the Riegl instrument appeared to be smoother than those with an intermediate number of samples (Impulse), which

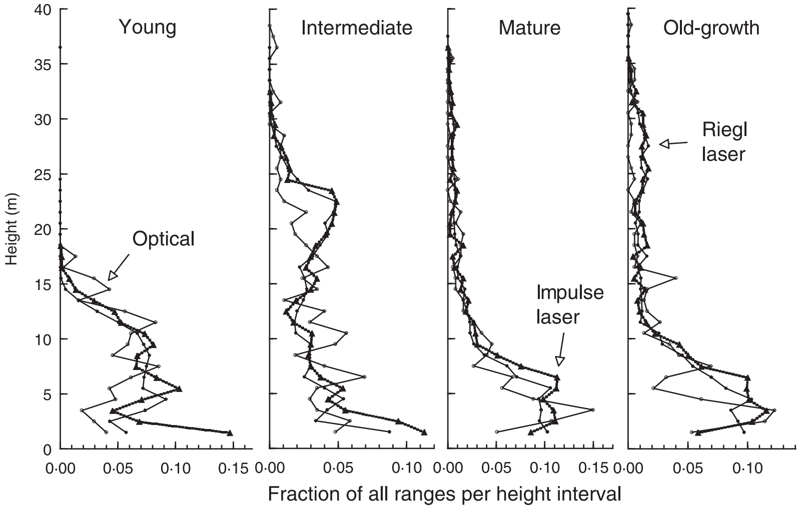

Fig. 6. Comparison of vertical range distributions obtained with three methods of obtaining distances, the optical point quadrat method (open circle), the Impulse LR 200 rangefinder (triangles), and the Riegl LD90-3100HS (filled circles), from four test stands.

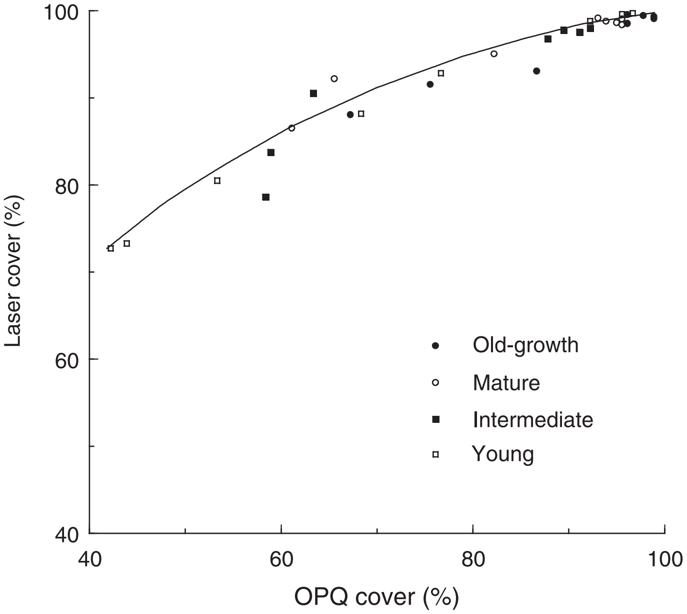

Fig. 7. Comparison of total cover measured with the optical point quadrat method and with the Riegl laser system, in four test plots.

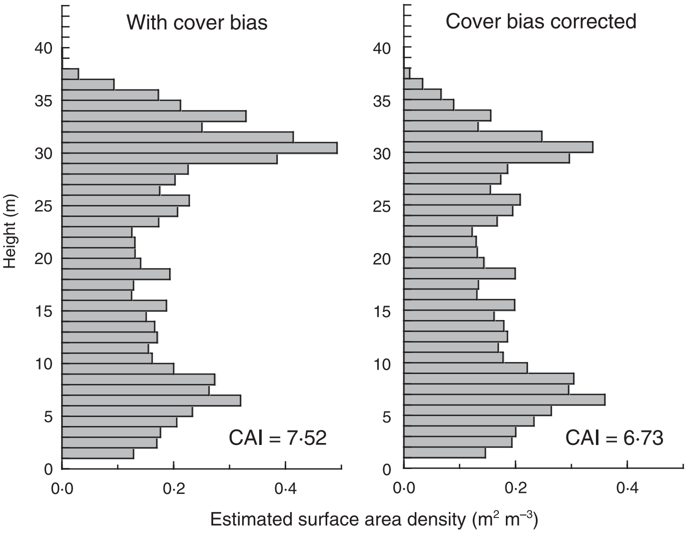

Fig. 8. Effect of cover bias correction on the mean canopy height profile in the mature forest test plot.

were distinctly smoother than those with the fewest samples (OPQ).

Canopy cover bias

To assess the bias of the system in assessing canopy cover, we measured cover using the OPQ method in each test plot with observations of foliage and non-foliage cover at 12 marked ground positions. Concurrently, we also employed the laser system on three parallel transects ($x = 0, 15, 30$) and cover was estimated as the fraction of non-sky ranges. The optical and laser cover observations were conducted on eight dates in each plot during the leaf abscission period, providing a range of leaf cover.

The laser system always overestimated canopy cover relative to that of the OPQ method (Fig. 7). The degree of overestimation was inversely related to the cover: the laser 'saw' relatively more cover when OPQ cover was low. We developed a relationship to correct the biased laser estimates of cover and then compared the corrected and uncorrected CHP.

The heights of the maxima of surface-area density remained the same when the cover bias was corrected, but the relative importance of the overstorey and understorey peaks shifted (Fig. 8). The total estimated CAI was smaller following bias correction. Both effects are because the M-H transformation is most pronounced as cover approaches 1. The degree of cover correction was small here because cover was high.

Location error

Knowledge of the three-dimensional location of the laser returns depends on the uncertainties in horizontal position as well as the height and direction of the laser. We assigned the position of the laser returns acquired

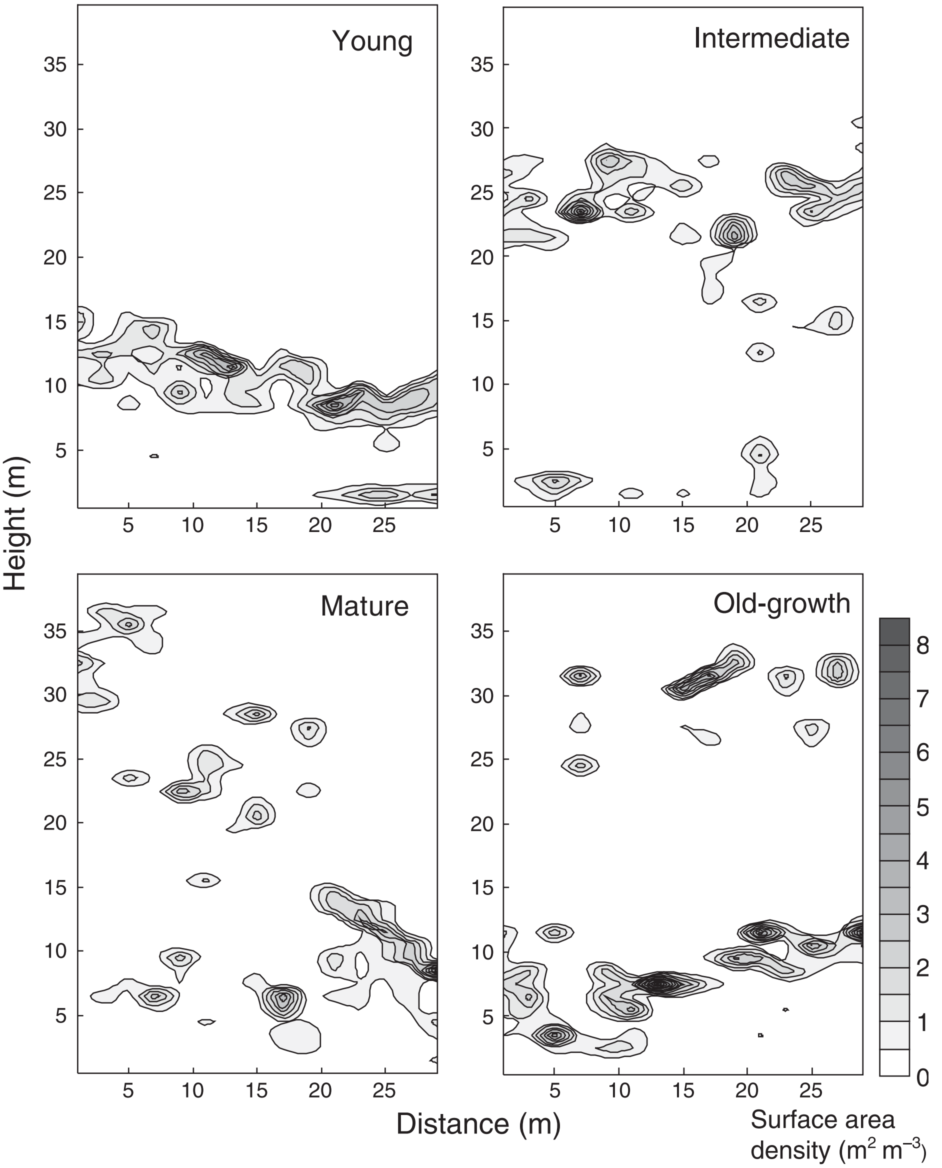

Fig. 9. Representative 30-m long height sections from midsummer transects in each of four forest stands of different developmental stage. Contours are estimates of surface area density. The data are taken from the central transect in each stand ($x = 15$).

while carrying the device by assuming a constant walking speed. Therefore, position accuracy was affected by the constancy of walking, which depended on terrain and obstacles. Walking speed variability among transects within a forest type, indicated by the coefficient of variation (= standard deviation/mean), ranged from 3·5% to 7·1% across field test plots at SERC. Variation in speed was somewhat greater among plots (9·3%). Walking speed also varied within a pace, but in one test this positional uncertainty was found to be low, 0·09–0·10 m (standard deviation of distance residuals).

Assignment of measurement position assumes that the laser is level, ranging directly overhead. We measured the pitch (forward and back) and roll (side to side) deviations from level along transects in the test plots. When walking at a typical speed the pitch and roll angles averaged 0·8–1·5° and 2·7–3·6° from vertical, respectively. The resultant total angular deviation varied from 3·1° to 4·5°. Deviations from level were less when walking slowly and greater when walking faster. When applied to measured distribution of ranges, these angles amounted to a horizontal uncertainty averaging 35 ± 31 cm in the young- and 54 ± 61 cm in the old-growth test plot. The repeatability of transect measurements was affected by all these factors.

VISUALIZATION OF DERIVED CANOPY STRUCTURE

The numerous field observations provided by the system can yield a variety of descriptions of canopy structure, depending on the manner in which it is deployed and the method of aggregating the canopy intercepts.

We deployed the system on transects walked along the forest floor. A horizontal-height section displayed as a contour plot is a convenient way to present the results (Fig. 9), these are akin to the axial tomography common in medical imaging. The grids in these height sections were

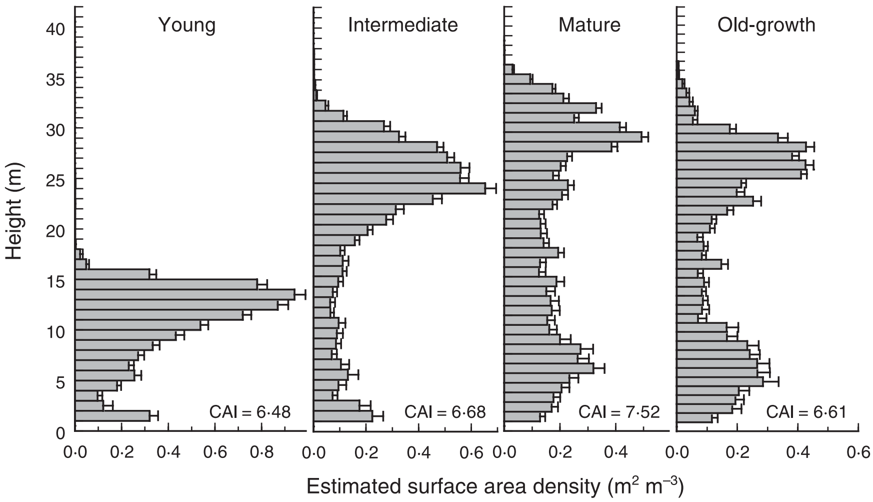

Fig. 10. Mean canopy height profile in 30 × 30-m sections of four forest plots at SERC taken with the rangefinder system. Error bars are standard errors. The canopy area index is given for each test plot.

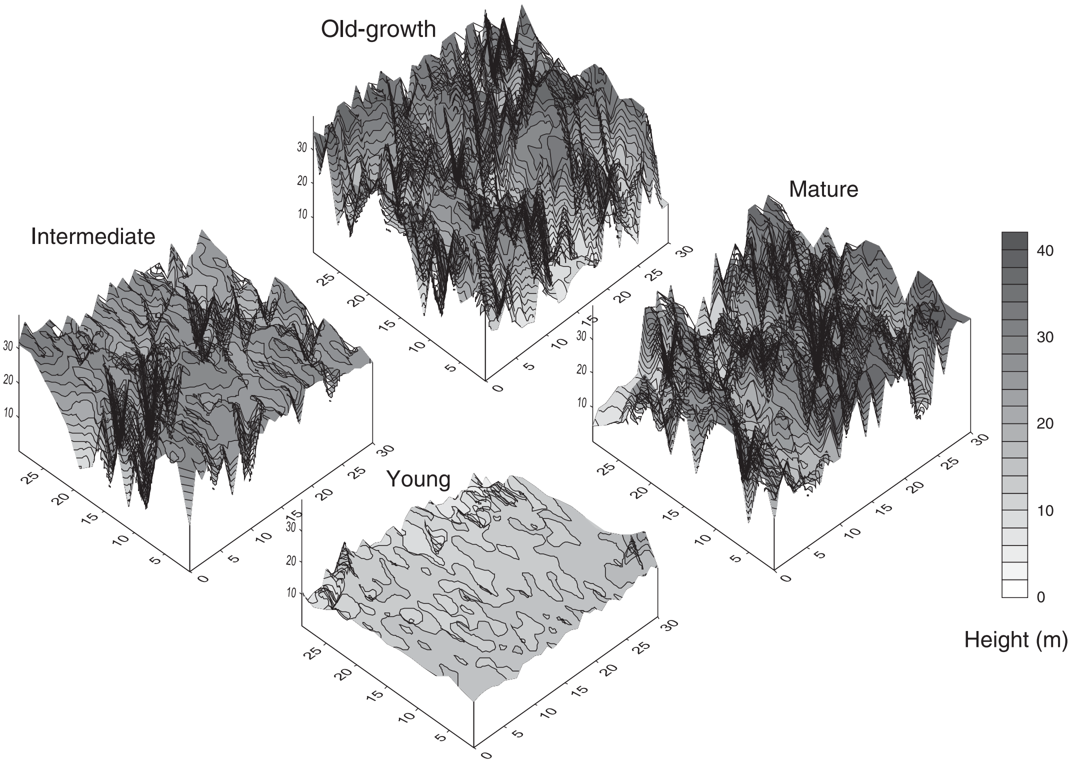

Fig. 11. Topography of the outer canopy from maximum heights from individual canopy height profile observations in each test plot, presented as a surface.

not interpolated; however, the contours were smoothed with a cubic spline (Golden Software Inc. 1999).

The vertical columns that comprise the height sections may be spatially averaged to yield the mean canopy height profile, C(h), and its variability (Fig. 10). The C(h) values, in turn, can be summed across heights to yield the estimated CAI.

The profiles in Fig. 10 are familiar representations of canopy structure that summarize much spatial information (Lusk & Ortega 2003). What is new is the capacity to estimate spatial variability (indicated by the error bars) and the scale of spatial covariance. Note that the pattern of uncorrected CAI among stands is similar to that of LAI (Table 1), with a maximum at the mature development stage.

Unless overlap is unusually severe, the high-speed system we describe usually samples the majority of heights overhead, including the topmost surface, the local outer canopy height (LOCH) (Parker *et al.* 2004), within each column. The ground-measured LOCH values are comparable to those obtained in a similar sequence of stands using a helicopter-borne system (Parker & Russ 2004). The shape of the outer canopy may be estimated from the spatial collection of LOCH values (Fig. 11).

The surfaces in Fig. 11 complement the aggregate CHP of Fig. 10. Both the mean and variability in canopy height increased during development of this forest type.

SUMMARY MEASURES

Canopy cover, CAI and LOCH were readily obtained from the data provided by this system. The porosity of the canopy and the size distribution of overhead openings could also be obtained. Indices of structural complexity, such as the foliage height diversity of MacArthur & MacArthur 1961), were easily calculated. Moreover, because the information acquired was location-dependent, it was possible to estimate variation, spatial covariation and spatial scale for each measure.

Discussion

The system we describe can be used to measure canopy structure, at 1–2-m resolution, over horizontal scales up to hundreds of metres. As used here, it rapidly gives information on the distribution of surface area in horizontal-height slices through forests. The results obtained are consistent with previous, more laborious methods. Because the commercial rangefinder at the heart of the system is not optimized for this application, it has some biases. However, we found these biases have relatively little effect on the resulting estimates of canopy structure when the system is deployed as described.

Novel information on the internal organization of vegetation is provided by the system. A variety of summary measures of structure and complexity have been suggested and visual representations have been presented. With more experience in using this system, more kinds of summary and visualization will emerge.

BIAS EFFECTS ON STRUCTURE ESTIMATES

The system does not discriminate targets smaller than 1 cm (when far away) to 0·3 cm (nearby). Many twigs and small branches are of these sizes but all leaves in the studied canopies are larger than this (Parker, O'Neill & Higman 1989). The system cannot penetrate through holes smaller than 4 cm (when far away) to 2 cm (when close). The effect of this bias is difficult to evaluate as the size distribution of apertures in canopies is not known. The current system averages a minimum of five ranges, potentially leading to fictitious targets. However, we found that when used at a normal walking pace under real canopies the effect of averaging different targets is small.

PRACTICAL LIMITATIONS

The system is awkward to use where walking straight lines at a constant speed is compromised, such as in young forests with high stem density, woods with numerous attached lower branches (such as some pine thickets) and older or disturbed stands with much debris on the forest floor. However, we have employed this system in a wide variety of canopies, from brushy clearcuts, to plantations, to very tall forests of *Sequoia sempervirens* (Hitchcock & Cronquist 1978) (where surfaces were detected to 95 m above ground).

POTENTIAL USES

The portable canopy rangefinder system can rapidly assess canopy structure at a variety of spatial scales, from the size of small plots (metres), to the scale of crowns and gaps (tens of metres) to that of whole stands and landscapes (kilometres). It could be used to inventory timber and biomass, and to characterize forest complexity and biotic habitats. It would provide a quantitative and more general alternative to the qualitative and idiosyncratic measures often used (Franklin *et al*. 2002). The capacity to quantify spatial variation, an important aspect of vegetation structure (Franklin & Spies 1991), is an advance over some previous methods.

The system could be used to quantify changes in canopy structure at various time scales. It could provide detailed assessment of canopy growth and allocation response to field experiments, including fertilization, irrigation, soil warming and fumigations with CO_2 (Hendrey *et al*. 1999) and O_3 (Nunn *et al*. 2002). It could be a tool for long-term studies of vegetation change. Such measurements could be used for investigation of interactions between structure and microclimate or of structure and atmospheric exchanges. Finally, the portability of the system could provide determination of vegetation structure in remote locations and could be a useful adjunct to rapid surveys, prompt assessment of damage from various disturbances and of the intensity of human modifications.

FUTURE DEVELOPMENT

Various instrument, operational and data analytical aspects of the system could be improved. The laser beam size could be reduced somewhat without compromising eye safety, the system would then be less sensitive to near targets and able to range through smaller apertures. The rangefinder might be modified to give full control over averaging so that the problem of phantom targets would disappear. Studies should be undertaken of the scale-dependence of the measurements (What sort of binning is appropriate in a particular situation?) and of repeatability (What level of 'noise' is unavoidable?). It will be useful to compare the views of canopy structure provided by this ground-based system with those obtained from LIDAR systems on airborne or space-based platforms. Finally, new means should be developed to summarize the data and visualize the results, such as three-dimensional renderings of the internal canopy architecture. Such studies and improvements will enlarge the scope of applications for the system we describe.

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