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Determining Forest Canopy Characteristics Using Airborne Laser Data

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A pulsed laser system was flown over a forested area in Pennsylvania which exhibited a wide range of canopy closure conditions. The lasing system acts as the ultraviolet light equivalent of radar, sensing not only the distance to the top of the forest canopy, but also the range to the forest floor. The data were analyzed to determine which components of the laser data could explain the variability in crown closure along the flight transect. Results indicated that canopy closure was most strongly related to the penetration capability of the laser pulse. Pulses were attenuated more quickly in a dense canopy. Hence the inability to find a strong ground return in the laser data after initially sensing the top of the canopy connoted dense canopy cover. Photogrammetrically acquired tree heights were compared to laser estimates; average heights differed by less than 1 m. The results indicated that the laser system may be used to remotely sense the vertical forest canopy profile. Elements of this profile are linearly related to crown closure and may be used to assess tree height.

Introduction

Technology which may assist in the accurate, precise, and timely assessment of forest canopy characteristics may prove valuable to those involved in forest mensuration. Operational approaches currently used to determine forest stand characteristics include airphoto interpretation to delineate homogeneous stands and ground survey techniques to measure the characteristics of that stand. Typically the end result is a quantitative forest description which, in conjunction with numerous other factors (accessibility, topography, watercourse proximity, etc.) provides an informative foundation for a forest management plan.

A profiling laser system gathers ranging (distance) data along the aircraft flightline. The time between the emission of a single laser pulse and the initial return is measured and converted to distance between the plane and the earth. Subsequent returns from that same pulse are measured; strong secondary returns may indicate a dense understory or the ground beneath a vegetation canopy. A succession of such measurements involving numerous, consecutive pulses may be used to develop a profile of the vegetation canopy and the underlying terrain along a ground transect.

A profiling laser system flown at relatively low altitudes along forested transects gathers data from which mensurational information may be derived. The profiling laser quantifies certain forest characteristics within a stand, taking measurements at the resolution of a small section of a single tree canopy. It is the purpose of this paper to (1) describe the lasing system, (2) describe the attributes of the data collected, (3) determine the

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strength of the relationship between the laser data, a measure of tree canopy density, and tree height estimates, and (4) draw inferences concerning the interaction of the laser pulses with the forest canopy.

Background

Much of the laser ranging work done to date has been done in the area of bathymetric profiling and mapping. Studies developing techniques to monitor coastal zone environments have taken advantage of the accuracy and precision of the laser measurements and the water penetration capabilities of the light pulse (Guenther, 1978). Water quality researchers have utilized the active system to fluoresce chlorophyll in phytoplankton to assess algal concentrations (see Klemas et al., in Kim and Ryan, 1973). They have developed techniques to monitor and characterize oil spills by inducing fluorescence in the pollutant and monitoring the multichannel response (Rayner and O'Neil, 1979).

The laser used in this study, initially developed and tested for such bathymetric work, was described by Hoge and Swift (1980). The terrain applications of the Airborne Oceanographic Laser have been studied by Krabill et al. (1980). Their work has shown that laser profiling data may be used to accurately assess terrain elevation. Contouring data derived from laser data and photogrammetric analyses agreed within 12–27 cm (0.4–0.9 ft) over open ground, and 50 cm in forested areas. Subsequent work has demonstrated that the profiling laser system can measure various forest canopy attributes, including tree heights, and hence can provide an accurate forest canopy profile. This profile is a 2-dimensional slice through the forest along the laser's ground track and involves an area measurement between two curves. The first curve is a trace of the terrain; the second, the top of the forest canopy (see Fig. 1). The area between the canopy and terrain curves can be calculated over any particular time period to derive the cross sectional area of the vegetation canopy. Work by MacLean (1982) indicated that the cross-sectional area of such a forest canopy profile was linearly related to the natural log of timber volume (R^2 values ranging from 0.70 to 0.90). He found that the cross-sectional area/ln(timber volume) relationship was species dependent; regression analyses not stratified by species resulted in weaker

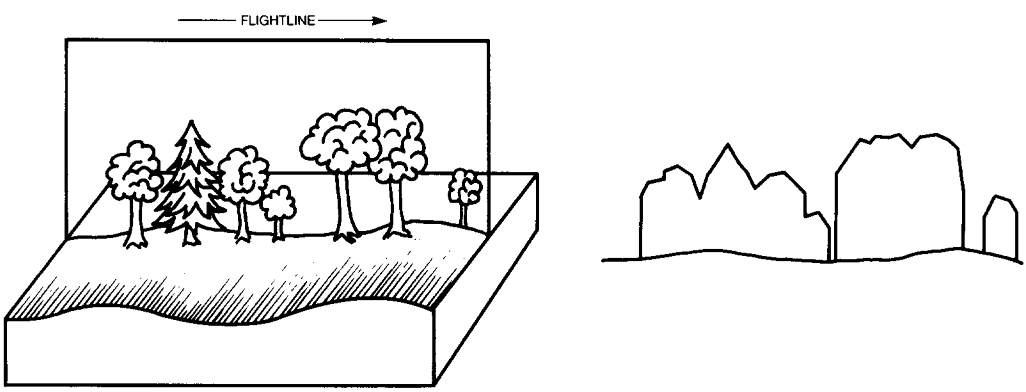

FIGURE 1. An example of a forest canopy profile which might be obtained via a laser profiling instrument.

relationships. Scientists working with the data suspected that laser response to the forest canopy was not only a function of tree height, but also of canopy density. In order to assess the validity of this hypothesis, a forested test site was selected which exhibited a wide range of canopy closure conditions.

Study Area

A flightline was located on Blue Mountain approximately 10 km southwest of Doubling Gap, in the Ridge and Valley province of south-central Pennsylvania. The flightline was located parallel to the southwest strike, for the most part along the top of the heavily forested ridge. The forests were typical Appalachian hardwood cover types, predominantly oak–hickory. Stands near the northern end of the flightline were, in general, healthy, and exhibited close to 100% canopy closure (i.e., an observer over the canopy looking straight down would see only tree canopy, no ground). Gypsy moth damage increased as one moved southwest along the flightline, and stands near the southern end of the 14 km flightline typically had all vegetation consumed (0% canopy closure).

The data were acquired 13 July 1981 between 10:30 a.m. and 12:30 p.m. EST. Clusters of red and white weather balloons were filled with helium and tethered above the treetops to mark the ends and midsections of the flightline. Strips of safety orange plastic were laid in the middle of woods roads at the flightline/road intersections.[1] A number of data collection passes were flown, all within ±100 m of the flightline markers.

System and Data Characteristics

The data collection system

The LIDAR system is a pulsed laser unit which can operate in either a profiling or scanning mode from an aircraft platform. Only profiling data were examined in this study, hence only the profiling data collection system is explained below. See Krabill et al. (1980) or Hoge and Swift (1979) for a discussion of the scanning system. In the profiling mode, the nitrogen laser can emit up to 400 pulses of light/s (wavelength 0.337 μm), and photomultiplier tubes measure the returns from each pulse. A portion of the pulsed energy is reflected back to the sensor when the target (such as a tree crown) is initially illuminated. A portion of this beam energy may continue through the canopy, eventually reaching the ground. Essentially 37 measurements are made on each pulse, each contains information pertaining to the vertical characteristics of the target. The electronics are such that, once the initial return is sensed for a particular pulse, a preset delay is triggered, after which 36 sequential measurements are made. The delay is set prior to the data collection overpass, and may be adjusted between overpasses while airborne. The 36 sequential measurements of the strengths of the secondary laser returns are made every 2.5 ns (1 ns = 10^{-9} s). The measurements are timed such that observations are taken on the strength of return every 1/3 m (vertical range). The 36 measurements then constitute a 12-m window within which the strengths of the secondary laser re-

[1] The pilots noted that, from their vantage point, the orange strips (approximately 1 m wide, 3–4 m long) were more conspicuous than the 1.3-m weather balloons.

turns are measured. This window is used in forested areas to "search" for a strong secondary ground signal from beneath the canopy after the top of the canopy is initially sensed. Two or more strong returns in the waveform may indicate the presence of a dense understory and the ground. The delay should be set for the average tree height found in the study area, or, perhaps more accurately, for those tree heights which one is most interested in sensing accurately. If the delay is too short (or the trees too tall), only returns from the lower portions of the tree canopy will be sensed within the 12-m window. Likewise no ground signal is sensed when the delay distance exceeds the tree height (i.e., trees too short). In either case, a strong ground response cannot be found and that tree's height cannot be calculated directly from the laser data (see Fig. 2).

The lasing system is currently housed, along with a computer and tape drive necessary to handle the appreciable data volume and rate, in a P-3A four-engine turbo-prop aircraft. The plane is flown 150–450 m above the terrain at a speed of approximately 100 m/s. At this speed, a pulse is emitted every 0.25 m along the flight path. Every 0.25 m, then (i.e., every 0.0025 s), the time between the pulse emission and the initial return is measured and the signal strength in each of 36 channels is measured (after a given delay). The laser footprint, or the instantaneous size of the area illuminated, depends on the height of the plane above terrain. The angular instantaneous field of view is 5 mrad; the footprint then is 0.75 m at 150 m flying height. Hence there is considerable pulse overlap between consecutive shots.

A 35-mm format camera loaded with black and white print film is used to photograph the entire flightline, obtaining one photograph every second. Stereoscopic coverage is not available; however the 1:600 scale photos may be used to assess canopy closure.

Laser data to assess forest characteristics

The aircraft laser data are preprocessed to integrate the various sources of positional, temporal, and signal strength information. Two concepts which are fundamental to this preprocessing step are that of "ground slant range" and "predicted ground slant range." The ground slant range is simply the distance from the plane to the initial point of illumination, be it tree canopy, shrubs, grass, bare soil. The predicted ground slant range is more abstract. On the basis of this predicted value, a particular pulse can be identified as having interacted with the forest canopy, with the ground, or with both. In general the predicted ground slant range is a previously measured distance and tolerance within which one would expect to find the ground signal on the next pulse, if the ground is sensed at all. An example might best explain this concept.

Example. Given that pulse P hit ground, the slant angle is S. Analyze pulse $P+1$ (the next pulse) which has a slant range of X. For pulse $P+1$, the predicted ground slant range (the predicted distance from the plane to the ground) is S. If X is within a certain tolerance (set by the operator prior to preprocessing the data, generally on the order of 2–3 m), then X is considered a ground return and becomes the predicted ground slant range for pulse $P+2$. Otherwise, S remains the predicted ground slant range for pulse $P+2$.

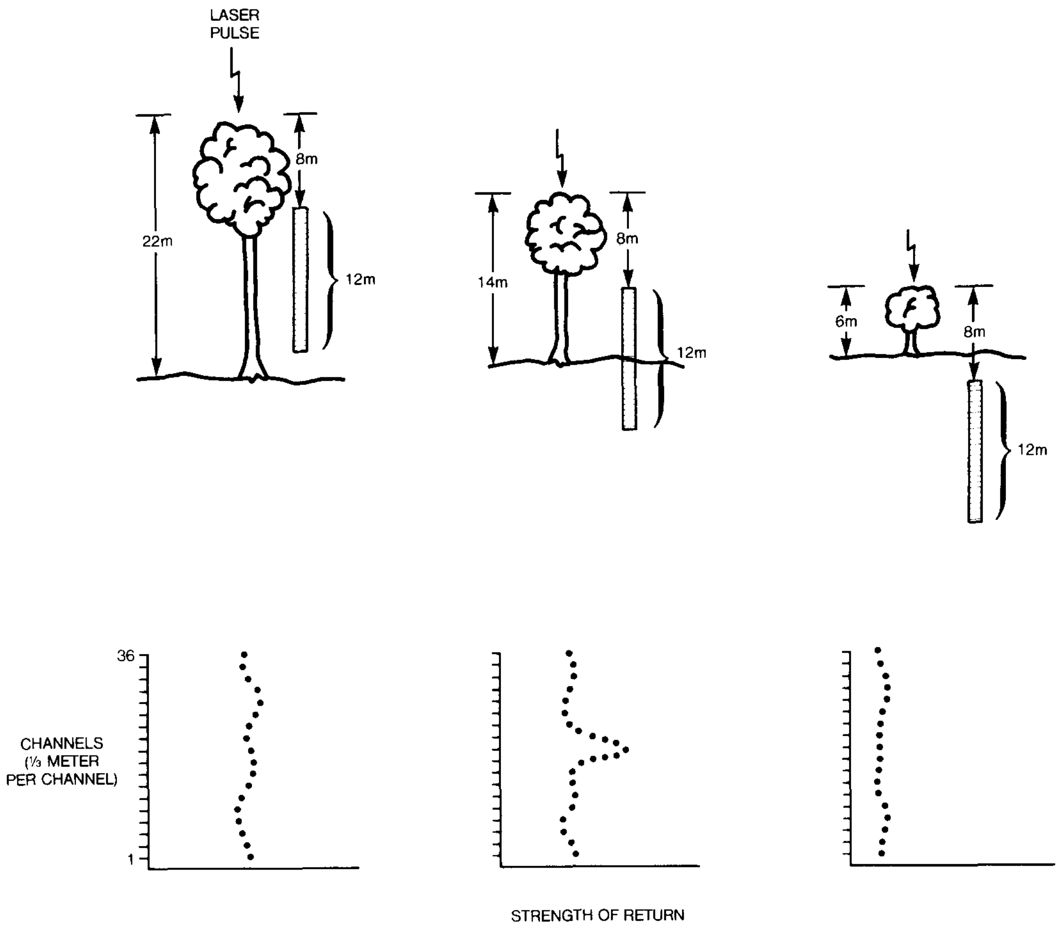

FIGURE 2. The effects of different tree sizes on the ability to detect the forest floor. Assume an 8-m (55-ns) delay.

Many of the variables rely on this predicted ground slant range concept; the definitions of these variables are given in Table 1.

The variables listed in Table 1 were analyzed to determine the strength of the relationship between the laser data and the forest canopy characteristics. These variables were regressed with airphoto-interpreted canopy closure estimates to determine those laser variables most strongly related to canopy closure estimates. Also, within the constraints imposed by the airphotos, photogrammetrically acquired tree height estimates were compared to laser estimates of average height.

Data analysis

The data from two passes were analyzed individually. The data for each pass were acquired along the same flightline; however, different ground transects were imaged since the aircraft cannot exactly duplicate a ground track. A 126-ns delay was used on both runs; hence the middle of the 12-m window was centered 18.3 m below the initial return. The laser information for each of the runs was subdivided and summarized in 1-s intervals.

TABLE 1 Laser Variables Derived from Flight Data[a]

Pulse variables
- a. total number of pulses: 400 pulses generated per second; anomalous pulses discarded
- b. number of pulses direct to ground: if slant range is within the predicted ground slant range tolerance, pulse judged to be a ground hit
- c. number of pulses hitting canopy: if slant range is smaller (i.e., the target is taller) than the predicted ground slant range, then pulse is in the canopy
- d. number of tree heights sensed from waveform: the pulse is a canopy hit and a ground return is sensed in waveform [see Fig. 2(b)]
- e. number of tree heights not sensed from waveform: the pulse is a canopy hit, but no strong ground return found in the waveform
- f. number of tree heights too short to sense from waveform: the pulse is a canopy hit, but the difference between canopy slant range and expected ground slant range is too small to permit sensing of ground [see Fig. 2(c)]
- g. number of tree heights too tall to sense from waveform: the pulse is a canopy hit, but the difference between the canopy slant range and expected ground slant range is too large to permit sensing of ground [see Fig. 2(a)]

Note: $a = b + c$

$c = d + e + f + g$

Power variables

canopy power: a relative measure (unitless) of the return strength of the signal from a canopy hit

ground power: a relative measure (unitless) of the return strength of the signal from a ground hit

Profile variables

tree height: difference between the canopy slant range and the ground slant range, calculated using pulses described in d

canopy cross-sectional area: area between the initial pulse hits and the ground

[a] All variables were tallied at 1-s intervals.

The 1-s intervals corresponded to the segments photographed with the 35-mm camera. Forest canopy measurements were made on each 35-mm black and white photo. The along-track fiducial marks delineated the approximate ground track of the laser. The area directly adjacent to and including the transect was assessed using a 25-point dot grid. Each dot was identified as either healthy tree canopy, defoliated tree canopy, a hole in the canopy, shrub, or open ground. Two photointerpreters assessed the 35-mm photographs independently and their assessments were averaged. Canopy closure was calculated from the averaged photointerpretation results:

$$\text{crown closure (\%)} = \frac{(\text{avg no. of points in healthy canopy})}{25} \times 100.$$

The variables listed in Table 1 were regressed against this canopy closure estimate for each flightline in order to determine those laser variables which best explained canopy variability.

In addition to the laser data/photointerpreted canopy closure regression analyses, height measurements from the two data sources were compared. Original plans called for stereoscopic measurements to be made at each of the 116 intervals located on the 1:6000 color infrared airphotos. Unfortunately, cloud shadow and the excessive relief displacement reduced this sample number to 15 photogrammetrically derived height measurements. Tree heights were calculated from stereo photo measurements of parallax. Parallax differences between the bottom and top of the forest canopy were measured using a mirror stereoscope and a parallax bar.[2] The complete height equation was used to calculate tree heights, since the use of the simplified equation would have resulted in appreciable errors due to significant differences in the average elevations of the photo baseline and the base of the tree canopy measured. The equation and definition of terms which follow may be found in Paine (1977):

$$h_o = \frac{[H-h-E][dP]}{P+[(E)(P)/(H-h)(E)]+dP},$$

where

h_o = Height of the object being measured,

$H-h$ = flying height above the two ends of the baseline (P),

E = difference in elevation between the base of the object and the average baseline (+ if base of object is higher than baseline, − if lower; estimated using topographic maps),

dP = difference in absolute parallax between the top and bottom of the object being measured (measured with a parallax bar),

P = absolute parallax of the baseline (average baseline length measured on both photos of the stereo pair).

The canopy heights so derived were compared to the respective average tree heights calculated using laser profiling data.

Results

Canopy assessment

Scatterplots of the laser variable/ canopy closure relationships, t-tests, regression analyses results, and plots of the canopy profile were studied to determine which laser variables were most closely correlated to forest canopy condition. The Biomedical statistical program P9R, All Possible Subsets Regression, was used to conduct the linear regression analyses (Dixon and Brown, 1979). The results of the regression analyses are given in Table 2. Since the best four variables explained 91% or more of that variability explained by all variables considered (nine), only the best one, best two, three, and four variable subsets are shown. Based on the results, the following observations were made.

1. The amount of healthy crown sensed over an interval is most closely related to the number of pulses which hit the tree canopy but in which a ground signal could not be found in the waveform (even though the 12-m window was positioned such that it could have picked up a ground return). This variable is abbreviated THNS (see Table 2, variable key). The failure to find the ground signal in the waveform connotes a dense canopy; the higher the number of such pulses, the denser the canopy. Similarly, a direct relationship exists between the number of pulses in which the ground was sensed beneath the canopy (THS) and photointerpreted canopy closure. THNS and THS are complimentary variables, and the inclusion of either one in a given variable set precluded use of the other.
2. A comparison of the healthy and defoliated laser profiles in Fig. 3 suggested that pulse penetration into a defoliated canopy is greater than that distance into a healthy canopy. If this observation is correct, then the num-

[2] The parallax bar was calibrated to tenths of a millimeter, interpolation capabilities to hundredths of a millimeter.

TABLE 2 Results of the Variable Selection Regression Analyses

One Var		Two Var			Three Var				Four Var				
1	Rsq	1	2	Rsq	1	2	3	Rsq	1	2	3	4	Rsq
Flightline 1													
THNS	0.53	THS	XSEC	0.60	THS	XSEC	BD	0.62	THNS	XSEC	THTS	BD	0.62
+		−	+		−	+	−		+	+	+	−	
Flightline 2													
THNS	0.45	THS	XSEC	0.62	THS	XSEC	GH	0.63	THNS	XSEC	THTS	GH	0.65
+		−	+		−	+	+		+	+	+	+	

[a]All variables listed explained significant variability in percent crown estimates (as judged by photointerpretation) at the 95% level of confidence. The positive and negative symbols report the sign of that variable's linear coefficient. Variable key: BD: big difference = no. of consecutive pulse pairs where the slant ranges differ by more than 5 ms; GH: ground hits (= no. of pulses direct to ground)/(total no. pulses); THNS: tree heights not sensed from waveform = (no. pulses where tree height not sensed from waveform)/(total no. of canopy hits); THS: tree heights sensed from waveform) = (no. pulses where tree height sensed from waveform)/(total no. of canopy hits); THTS: tree heights too short = (no. pulses in which tree heights are too short to sense ground in waveform)/(total no. canopy hits); XSEC: cross-sectional area = area between top of canopy and terrain.

ber of pulses in which the trees were too short to allow sensing of a ground signal in the waveform (THTS, see Table 2) should increase. A one-sided t-test (95% level of confidence) indicated that the number of such pulses were significantly higher in the defoliated canopy sample. For the sample chosen, the calculations indicated that, on the average, a pulse would have to penetrate at least 4.3 m further into the defoliated canopy in order to produce the results found.[3]

3. Cross-sectional area (i.e., the canopy profile) increases as canopy density increases. Denser canopies intercept the laser pulse higher in the canopy; hence the cross-sectional area is directly related to canopy closure.
4. A t-test also revealed that the numbers of ground hits increased significantly in defoliated canopies (95% level of confidence). The fact that the number of ground hits increased in defoliated stands may be substantiated by comparing Figs. 3(a) and (c). The number of ground hits proved to be important in the regression analyses; however, its role was secondary to that of THNS for explaining canopy closure.
5. A measure of the "raggedness" of a canopy [see Figs. 3(a) and (c)] explained significant variation in crown closure estimates. As canopy closure increased, the number of consecutive pulse slant ranges which differed by more than 5 m (BD) decreased. Hence the degree of pulse penetration in a defoliated canopy varies greatly relative to a healthy canopy which intercepts the pulses at the top of the tree crown.

The R^2 values derived from the regression analyses, which seem low, should be viewed in context. This study compared

[3]Penetration distance calculated as follows. Given: delay: 126 ns = 18.3 m; waveform range: 12 m centered 18.3 m below the initial return; average height of the stand investigated (from healthy canopy): 16.6 m. Then, in order to "push" the waveform completely into the ground, the pulse would have to travel [(12 m)/2] − (18.3 − 16.6 m) = 4.3 m further, on the average.

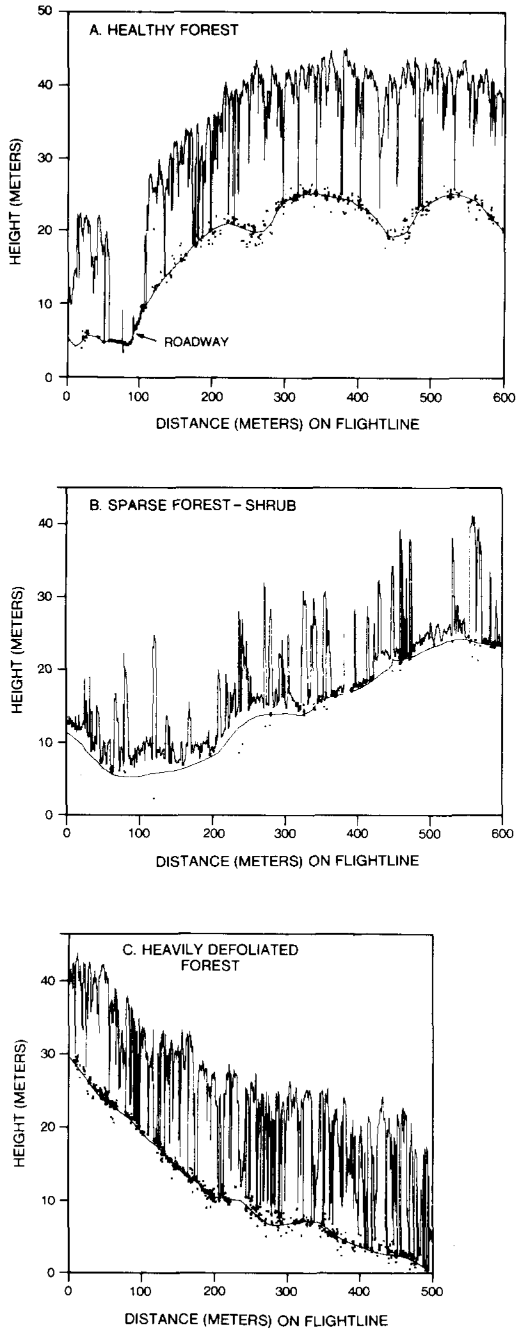

FIGURE 3. Comparison of laser data (first overpass) obtained over (a) healthy forest, (b) a nonforested area, and (c) a heavily defoliated forest. The solid ground line was digitized by an operator following known ground hits in the laser data. The digitized ground slant range served as the expected ground slant range.

laser information to photointerpreted data. Very specific quantitative information obtained along a narrow ground transect (0.75 m) was compared to subjective assessments of canopy condition along a necessarily much wider swath (7–8 m). Two factors should be considered when evaluating the results of this study. First the photointerpretation estimates of canopy condition are subjective. In order to gain some estimate of the reproducibility of the photointerpreted data, canopy closure estimates were regressed for each flightline for photointerpreters 1 and 2. The R^2 values were 0.81 and 0.82 for flightlines 1 and 2, respectively. The results indicate that there were discrepancies between photointerpreters using the same dot grid on the same photos. The photointerpreted data, then, serves as a relatively gross estimator of canopy condition. Second, the exact location of the laser ground track could not be pinpointed on the photos. Changes in the attitude and altitude of the aircraft, terrain relief, and the lack of numerous local landmarks in this heavily forested region made flightline location an exercise in approximation. Photo estimates of crown closure assessed average crown conditions in the general area of the actual ground track (within ± 20 m). The information presented in Table 2, then, may best serve to indicate relationships and trends, and should not serve as an absolute measure of the ability of the laser system to describe the forest scene.

Tree heights

Tree heights were determined using the 1:6000 color infrared aerial photography, a parallax bar, and a mirror stereoscope. Due to cloud cover problems and exces-

TABLE 3 Comparison of Tree Heights from Aerial Photography and Laser Data for Flightlines 1 and 2[a]

	Airphoto Interpretation	Laser Flightline 1	Laser Flightline 2
Mean (m)	16.79	16.53	16.23
Standard deviation	2.94	1.54	1.17
Range	11.9–23.5	14.3–19.0	13.8–18.5

[a]Number of samples is 15 for each flightline.

sive relief displacement, only a limited number of samples could be obtained from the photos. Table 3 presents the results of the tree heights analysis. The laser data described average tree height along 100 m of flightline (1-s flight time) as calculated from the waveform data. The photointerpreted data described the canopy height at the midpoint of the 100-m groundtrack.

The mean tree heights are comparable, though the variability and range of the airphoto interpreted data are twice as large. The increased variation of the photointerpreted data is a function of the method. Parallax determinations of canopy heights may be considered accurate only to within 10% of the true height due to the inability of the photointerpreter to precisely measure dP.

Discussion

A profiling laser system provides a method of determining canopy characteristics by quantizing the canopy profile. In this study the laser data were compared to ground conditions assessed using aerial photography. Although the ground reference data (airphoto interpreted information) were crude, relationships were found which explained the laser/canopy interaction.

Results showed that, as one would expect, a dense canopy attenuates the laser pulse more quickly than a defoliated canopy. The pulse penetrates further into a defoliated tree; as such the number of "short" trees and the number of ground hits increase significantly in the defoliated areas. These variables, however, are of secondary importance for describing canopy closure. Only 6% of the pulses were ground hits, and only 11% were hits on "short" trees (a portion of those defoliated). The majority of the pulses, 47%, were intercepted in the upper portions of the defoliated canopy.

Photointerpreted estimates of crown closure, then, were best explained by the ability to find a ground signal in the waveform data which accompanied each laser pulse. The inability to find a strong ground return after initially sensing the canopy connoted dense canopy cover. Conversely, a defoliated canopy allows more of the laser beam to penetrate to the ground, a strong ground return was measured in the waveform, and the ground power signal was stronger.

Tree branches and twigs intercept the laser pulse in a defoliated forest; a full flush of leaves return the pulse in healthy forest. Though one might expect substantial differences in the amount of ultraviolet light reflected back to the aircraft, the difference in the power return from a defoliated canopy amounts to less than 10% of the "nominal" healthy value. The substantial footprint size (0.75 m at the ground; 0.65 m at the top of a 20-m tree) and hardwood twig reflectivity may explain the pulse interception capability of the defoliated canopy. Hence the ability to discriminate canopy density differences depends more on the rate of attenuation of the signal through the canopy rather than the number of pulses which traverse the canopy without intercepting it. A smaller footprint would probably be advantageous since the effects noted in this study—increased ground hits, higher ground power signal, defoliated canopy penetration—would be exaggerated. Unfortunately, the smaller footprint size would negate the eye safety aspect of the current system.[4]

The profiling laser system integrates platform position and laser pulse information to produce a concise description of the forest along the ground track. The 1981 state-of-the-art system is limited, however, and these limitations impact the user. The useful, vertical working envelope of the laser is 150–460 m (500–1500 ft) during the day. The lower bound is set by Federal Aviation Administration regulations [at night the lower limit increases to 305 m (1000 ft)]. The upper bound is limited by the power of the laser system. The data rate is inversely proportional to the power of the pulse. At 400 pulses/s, there is not enough power to gather reliable returns above 460 m (this limit also increases at night since the daytime 0.337 μm bandpass filter is removed). The P-3A cannot safely fly over areas with sharp relief greater than 200 m and still maintain the operational envelope. For instance, flying along the ridgelines at Doubling Gap presented no problem, but the plane could not have safely or reliably collected data flying perpendicular to the 300-m ridges. A second limitation is the 12-m window. This window (36 channels) has been hard wired into the lasing system, and it would take appreciable effort to change the number of channels or the resolution of the window. Hence, the analyst must have a preconceived idea (i.e., *a priori* knowledge) of the average height of the canopy in the study area. Improvements in microcircuitry will undoubtedly remove these limitations.

[4]The system as currently configured is eye safe at 150 m. Beam concentration would preclude the safe use of this instrument.

Information concerning canopy density is available and laser data/canopy condition relationships were described. However, the strength of the laser data/ground condition relationship could not be assessed adequately using the photointerpreted data. The sample-intensive data, nominally one pulse every 0.25 m along the ground track, offers concise information concerning (1) tree height and (2) canopy profile. To link these data with standing biomass estimates, additional information is needed. The relationship between canopy profile and timber volume is based on stratification by species (MacLean, 1982). In order to obtain reliable information concerning timber volume, the tree species being lased must be known. Current research efforts address the capability to identify tree species based on fluorescence data. If species can be accurately identified using laser data, a remote sensing system capable of transect-sampling large forested areas quickly may be envisioned.

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