A Portable Airborne Laser System for Forest Inventory

Ross Nelson, Geoffrey Parker, and Milton Hom

Abstract

A simple, lightweight, inexpensive, portable airborne laser profiling system has been assembled from off-the-shelf, commercially available components. The system, which costs approximately $30,000, is designed to fly aboard small helicopters and single- or twin-engine high-wing aircraft without airframe modification. The system acquires first-return range and amplitude measurements at data rates up to 2000 hz (operator-controlled) and has an operational envelope up to 300 m above terrain. The airborne laser profiling system includes the laser transmitter/receiver, differential GPS receiver, a CCD video camera and recorder, and a laptop computer which interleaves and records the GPS and laser range/amplitude data. The portable airborne laser system (PALS) was designed to acquire forest height measurements along linear flight transects in order to conduct regional or subcontinental forest inventories worldwide. This economical laser system now puts airborne laser mensuration within reach of operational foresters and researchers interested in making rapid forest structure and/or timber surveys in remote areas. PALS has been used to acquire over 5000 km of flight transect data over the state of Delaware.

Introduction

Airborne lasers may be used to acquire ranging data to measure tree heights. The tree height data may be used directly to measure such forest biophysical characteristics as average canopy height, height variability or canopy roughness, and canopy closure (Arp *et al.*, 1982; Nelson *et al.*, 1984; Aldred and Bonner, 1985; Schreier *et al.*, 1985; Ritchie *et al.*, 1992; Ritchie *et al.*, 1993; Nilsson, 1996; Næsset, 1997a; Blair *et al.*, 1999; Means *et al.*, 1999; Means *et al.*, 2000; Popescu *et al.*, 2002). These height and density measurements, in turn, can serve as the independent variables in predictive models to estimate forest basal area, merchantable volume, biomass, and carbon (Maclean and Krabill, 1986; Nelson *et al.*, 1988a; Nelson *et al.*, 1988b; Nelson *et al.*, 1997; Næsset, 1997a; Næsset, 1997b; Lefsky *et al.*, 1999a; Lefsky *et al.*, 1999b; Popescu *et al.*, 2000).

A wide variety of laser systems now exist, and numerous researchers are investigating uses of these systems with respect to forestry applications. Originally designed for bathymetry (Hickman and Hogg, 1969; Hoge *et al.*, 1980), airborne lasers were first applied to terrestrial concerns throughout the 1970s (Link and Collins, 1981; Hoge *et al.*, 1983; Krabill *et al.*, 1984). Over the past 30 years, the technology has moved from research to commercial applications (Baltsavias, 1999). Applications include the use of airborne laser data for creation of digital terrain models, monitoring power lines, urban area mapping, and land-cover surveys (e.g., http://www.airbornelasermapping.com, last accessed 26 August 2002). Numerous commercial companies now offer turnkey airborne laser scanning systems or for-hire airborne laser data collection.

Applications of laser technology to forest inventory problems, however, remain largely in the research arena, for the following reasons:

- Laser data post-processing to derive inventory estimates requires the attention of specialists and, frequently, the application of specialized, home-grown software;
- Although forest/laser research has been ongoing for at least two decades, it is only in the last few years that researchers have demonstrated beyond a reasonable doubt that laser data can be used to create reliable maps of tree height, canopy density, biomass, and volume; and
- The flight hardware, to this point, has been expensive.

Certainly, some of the more sophisticated commercial and research laser scanners maintain price tags in the million dollar plus range. Research systems such as SLICER (Scanning Lidar Imager of Canopies by Echo Recovery; Blair *et al.*, 1994; Harding *et al.*, 1994), LVIS (Laser Vegetation Imaging Sensor; Blair *et al.*, 1999), AOL (Airborne Oceanographic Lidar; Krabill *et al.*, 1984), and EAARL (Experimental Advanced Airborne Research Lidar) are experimental, one-of-a-kind systems that are designed to push technological envelopes rather than to be cost-effective. Commercial airborne lasers currently sold are sophisticated, turn-key scanning systems used primarily to create accurate airborne digital elevation models (DEMs). These laser scanning systems record precise range and positioning data so that georeferenced DEMs can be produced. Some commercially available, airborne laser scanning systems host multi-return receivers. Data from these multiple-return, laser scanning systems can be used to make DEMs of the top of the forest canopy, the ground, and significant subcanopy layers. Commensurate with this level of sophistication are price tags of hundreds of thousands of dollars, which effectively puts these data out of the reach of operational foresters.

The authors, being interested in the uses of laser data for large-area forest inventory and forest canopy characterization, set about to design a simple, inexpensive, portable airborne laser system. Their objective was to design, build, test, and

---

R. Nelson is with the Biospheric Sciences Branch, Code 923, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 (ross@ltpmail.gsfc.nasa.gov).

G. Parker is with the Smithsonian Environmental Research Center, 647 Contees Wharf Road, P.O. Box 28, Edgewater, MD 21037-0028 (parker@serc.si.edu).

M. Hom is with Science Systems and Applications, Inc., Code 923, Biospheric Sciences Branch, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 (mhom@pop900.gsfc.nasa.gov).

Photogrammetric Engineering & Remote Sensing
Vol. 69, No. 3, March 2003, pp. 267–273.

0099-1112/03/6903–267$3.00/0

operate an airborne laser profiling system, not married/dedicated to any particular airframe, that could be used to structurally characterize and inventory forests. It is their hope that this type of system (1) will make airborne laser hardware economically more accessible, and (2) will allow scientists to conduct laser investigations in isolated locales far from home, e.g., the circumpolar boreal forests, South America, the Congo, and Asia. This report describes the result of their efforts to build a small, robust airborne laser profiling system.

System Description

With rapid technological advances, electronic miniaturization, orders-of-magnitude increases in computing speed and data storage capability, and software advances, systems with price ranges in the tens of thousands of dollars are appearing. The laser system herein presented was designed with the following priorities paramount: portability, simplicity, low cost, ease of operation, and applicability to forest/vegetation applications. To this end, the Portable Airborne Laser System (PALS) was designed using only commercially available components, including

- a near-infrared laser transmitter/receiver to measure first-return ranges and amplitudes from laser to target;
- a differential Global Positioning System (dGPS) receiver to monitor aircraft location;
- a charge-coupled device (CCD) video camera with GPS video titling and video recording to maintain a time/location synchronized video record of the flightlines;
- a laptop computer to record the digital dGPS and laser data; and
- a commercial software package to control, monitor, and record the dGPS and laser data streams.

Each of these components is described in some detail below. Name brand hardware and software packages and the approximate cost at the time of purchase (1999) are noted so that the reader can reproduce the system exactly. Certainly, other components can be used to construct a PALS-like instrument, and company names are mentioned only as a starting point and are not meant to imply exclusivity or highest quality. System components are shown in Plate 1, and a summary of the PALS components are reported in Table 1.

Cockpit Instrumentation

External Package

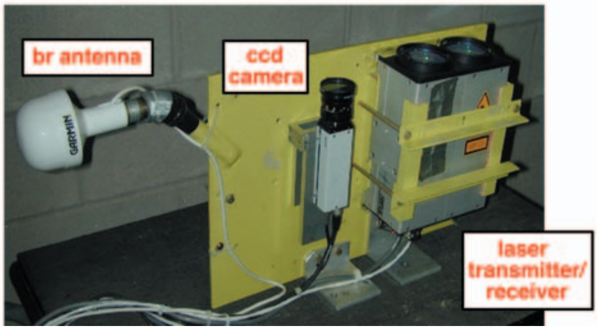

Plate 1 Components of the Portable Airborne Laser System.

Laser

A class IIIB, non-eyesafe, near-infrared (0.905 μm), pumped diode laser transmitter/receiver is used to collect range measurements from the flight platform to the target. The laser is eyesafe when operated from a moving platform. The Riegl LD90-3800-VHS laser, which comprises the heart of the PALS system, accounts for approximately half of its cost. The transmitter (i.e., pulse generator) emits a 20-ns (full width, half max.), 500-nJ, near-infrared pulse at 2000 hz. The laser can be programmed by the analyst to measure range to first target or range to last target. Company specifications for this laser report ranging accuracy on the order of 2.5 cm (http://www.riegl.co.at, last accessed 26 August 2002; see laser altimeters - LD90-3 series). Unfortunately, the laser employed in this study cannot be toggled such that first-, then last-return ranges are measured sequentially, though such lasers are available today. The laser can be configured to provide amplitude (i.e., strength-of-return) measurements, and can be programmed to run freely (laser-initiated firing) or to be triggered digitally, i.e., computer-initiated firing. Finally, the laser can be set up to average pulses (standard mode) or to collect individual pulses at 2000 hz (high speed mode).

As currently configured, PALS is a first-return, free-running, high speed, 2000-hz transmitter. The receiver detects the return pulse and generates a 4-byte serial stream where the first three bytes record the range and the fourth byte reports the strength of the return from the laser shot on a 0 to 255 scale. At 2000 hz, the laser outputs a serial stream at 64,000 baud, so the serial port handling the laser data must handle at least that baud rate in order to capture the data. The firing rate of the laser cannot be adjusted; it is always running at 2000 hz. The high-speed laser data stream can only be subsampled or averaged on the computer side or averaged, in standard mode, onboard the laser.

The transmitter has a 2-mr divergence and 10-cm optics so that, at a nominal flight altitude of 150 m, the system is illuminating a 0.3-m spot on the ground. Ground speed and the laser sampling rate determine the horizontal (i.e., along-track) post spacing between sequential laser shots.

Differential GPS

The PALS system employs a handheld GPS satellite receiver and beacon receiver for on-the-fly differential correction. A Garmin GPS III satellite receiver with a remote antenna is used to acquire signals from the GPS satellite constellation, and a Garmin GBR-21 beacon receiver is used to acquire land-based signals from U.S. Coast Guard dGPS beacons scattered across the U.S. (http://www.navcen.uscg.gov, last accessed 26 August 2002). The GPS III updates differentially corrected position information - latitude, latitude, longitude, elevation above mean sea level (MSL), speed, heading, Greenwich Mean Time (GMT), and signal quality metrics - once every two seconds. In the event that a beacon signal is not available, the system collects non-differential GPS data. The serial stream is sent simultaneously to a video titler (discussed below) to be incorporated into the video stream and also to a second serial port on the computer to be interleaved with the laser ranging data.

Plate 2 PALS mounted beneath a Bell 206 JetRanger.

Video System

A video history synchronized with the laser data is acquired with a CCD camera mounted next to and boresighted with the downward-looking laser. The Pulnix TMC-7 color camera refreshes every other line in the 768 column by 494 line pixel array at 60 hz, effecting a complete refresh every thirtieth of a second. A 16-mm, manually focused and shuttered lens fronts the camera. The focus is set to infinity, and on all but the darkest flights, i.e., dusk or dawn acquisitions, the *f*-stop was set at *f*16. Bright afternoon sun with an *f*11 setting would saturate the camera over bright targets, e.g., concrete and dirt roads. At 150 m AGL (above ground level), the 16-mm lens has a field-of-view of 60.5 m along-track by 45.4 m across-track. At a flight speed of 180 km/hr (50 m/sec), the image remains sharp, and individual tree crowns are easily discerned.

The camera picture is routed to a video titler which accepts both the S-video signal and the ASCII string from the GPS III satellite receiver. The GPS ASCII string is the same as that written to the dGPS/laser file, so that the video and computer data records are synchronized. The Horita GPT50 GPS video titler integrates the two and labels the video stream with the current latitude, longitude, GMT, various measures of GPS signal quality, internal (local) time, and date.

The annotated video stream is then routed to an 8-mm video cassette recorder (Sony AV500). The 8-mm tapes record approximately 2 hours of flight data. The VCR also records the cockpit conversation via a jack from the internal helicopter communications system to the audio jack on the VCR.

Computer

Two serial data streams, laser and GPS, are interleaved and recorded on a laptop personal computer with a 12-GB hard drive, 384 MB of RAM, and two serial ports; one internal and one on a PCMCIA card. In the aircraft, the computer runs on battery power alone, so a total of four 2.5-hour batteries were purchased, enough to last for an entire day's mission (batteries were partially recharged at every fueling stop). A typical 10-hour day's mission collected on the order of 50 to 75 MB of data. With an effective storage capacity on the computer of 10 GB, the computer could store 130 to 200 days worth of data. Typically, however, the data were backed up nightly onto 100-MB zip drives.

Data Collection Program

LABView™, a software package designed to control and collect data from a myriad of scientific instruments, was used to record the laser and GPS data. A LABView™ program, called a VI (or Virtual Instrument), was written (1) to ingest the 2000-hz laser data stream and the 0.5-hz GPS data from the serial ports; (2) to translate the 4-byte laser observations into character strings of range and amplitude; (3) to strip the appropriate GPS information from the GPS III serial stream; (4) to subset the 2000-hz laser data stream, i.e., process every pulse, every other pulse, every third pulse, . . ., every 50th pulse; (5) to display range, amplitude, and GPS data, real time, on the computer

Table 1. Portable Airborne Laser System Components. Costs Are in 1999 US Dollars (inc. = included in price)

Subsystem	Component	Description	Cost(USD)
laser range-finder	Riegl LD90-3800-VHS laser	2000-hz, near-infrared transmitter/receiver	16,150
video system	Pulnix TMC-7	video camera	900
	14-mm lens	manual focus/shutter	140
	clear filter	protective lens cover	20
	Horita GPT50	GPS video titler	590
	Sony AV500	8-mm cassette recorder	870
	Sony NP-F950	9-hour battery for AV500	150
dGPS system	Garmin GPS III	satellite receiver	400
	Garmin GA26	remote satellite antenna	40
	Garmin GBR21	beacon receiver	400
	Garmin GBR21	beacon antenna	165
	Garmin GPS45	power/data cable	50
computer system	Dell Inspiron 7000	12-GB Hard drive, 128-MB RAM	6,000
	PCMCIA card	two additional serial ports	inc.
	three batteries	2.5 hour each	inc.
	LABView	software package	2,500
power system	Artesyn BXB100	18- to 36-vdc to 12-vdc power converter	150
Total Cost of Hardware (excluding aircraft mounting costs):			**28,525**

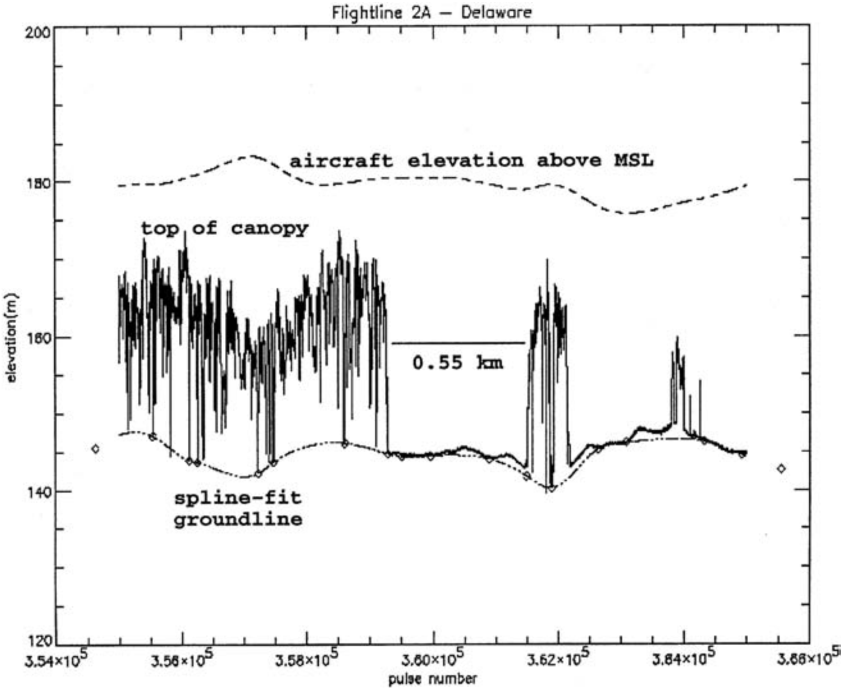

Figure 1. A 2.5-km section of flightline in Delaware. The ground line is a spline fit to local minima. The aircraft elevation is offset (i.e., reduced) by 120 m to permit plotting on the graph.

screen; and (6) to record a GPS-only file (for later use in GIS programs) and a separate laser file with GPS records interleaved.

The program, i.e., the VI, has a number of operator-defined controls that may be altered by the PALS operator during data acquisition. The operator can control and change the rate at which the 2000-hz laser data stream is subsampled. The operator can also adjust the graphics to size and position the trace of the laser ranges, i.e., the laser profile, on the screen. All of these settings can be changed on the fly while the VI is running.

Power

Much of the airborne laser profiling system runs off aircraft power. The Bell JetRanger's 28 vdc power supply was tapped and converted to 12 vdc for use by the laser, video titler, GPS system, VCR, and CCD camera. Only the laptop runs on its own internal batteries. PALS, minus the laptop, draws approximately 4 amps at 12 vdc. The aircraft power, converted to 12 vdc, is distributed to the laser, GPS receiver, and video systems through the power hub noted in Plate 1.

PALS was designed specifically for forestry applications. The system measures relative, i.e., local, heights, and PALS records locations which can be used to approximately position the flightlines on the ground or in a GIS to within 10 meters. The system does not measure absolute elevations, i.e., heights above an invariant datum such as MSL, nor does it record the location data needed to position the laser trace on the ground with sub-meter precision. Sub-meter *X, Y, Z* locations would require the inclusion of a centimeter-level dGPS system (cost in the $10k to $15k range) and a tiltmeter or INS system capable of measuring aircraft attitude changes on the order of tenths of a degree.

Data Collection and Performance

PALS was fitted to a cargo hook frame beneath a Bell 206 JetRanger (Plate 2) and was used to collect approximately 5000 km of flight data over the state of Delaware. The flight profile followed in Delaware is reported in Table 2.

During a data collection mission, the operator controls the airborne profiling laser by turning on the laser and initiating the LABView™ program enroute to the flightline starting point. The operator is provided with running traces of the first-return range and amplitude as well GPS position, speed and altitude information, updated every 2 seconds. The range from aircraft to the first target is subtracted from a constant so that a realistic, not inverted, profile is presented to the operator, i.e., so that trees "grow up" from the ground instead of "into" the ground. An illustration of the type of data collected by PALS is presented in Figure 1.

A number of forest structural measurements can be extracted from discrete segments of the profiling data with little effort. Height measurements include average canopy height, height variance, quadratic mean height, maximum height(s), and various decile or quartile heights. The ratio between tree

TABLE 2. FLIGHT PROFILE AND INSTRUMENT SET-UP FOR THE DELAWARE OVERFLIGHTS

General:	5000 km of flight data acquired June–August, 2000, 5 days. 56 systematic, N-S flightlines 1 km apart; longest: 163 km shortest: <1 km Cumulative flight time, including transit: 49 hours over 5 days Flight Costs: ~ $30,000 USD
Nominal flight altitude AGL:	150 m
Nominal flight speed:	50 m/sec (180 km/hr, 97.2 knots)
Laser subsampling interval:	10:1
Effective laser firing rate:	~200 hz
Effective post spacing:	0.25 m
Laser spot size (2 mr divergence):	0.3 m

hits and ground shots yields canopy density. Canopy roughness can also be quantified by calculating height variance or rumple, where rumple is the distance traced over the canopy divided by the horizontal distance along the flight segment. Many of these profiling variables have been shown to be correlated with forest volume and biomass (Nelson *et al.*, 1988a; Nelson *et al.*, 1988b; Nelson *et al.*, 1997; also the Delaware inventory results, not yet published). Coefficients of determination, however, are typically in the 0.5 to 0.6 range due to the fact that height is not a good predictor of volume or biomass; tree diameter is the predictive driver.

In order to assess the stability of the PALS, the system was bench-tested for two one-hour periods at the Goddard Space Flight Center after the U.S. Department of Defense had stopped dithering the GPS signal. The test was run to quantitatively assess (1) the locational stability of the GPS system (both differentially corrected and uncorrected), (2) the stability of the free-running laser's firing rate, and (3) the power stability of the laser as described by the strength of the laser return from an unchanging target. Table 3 reports the results from the two one-hour tests.

The results presented in Table 3 quantify characteristics which limit the utility of this laser profiling system. The system acquires highly accurate ranging data from the aircraft to first target, but the locational inaccuracies of the aircraft and the profile track are on the order of 10 meters in *X* and *Y* and 10 to 20 meters in *Z*. PALS data should be used to measure local height differences, e.g., tree heights. It cannot be used to gather anything more than gross topographic information because the aircraft position and laser pulse positions may be off by 10 m or more. These errors could be reduced below 1 m by incorporating an inertial navigation system or tiltmeters and a dGPS system which works with local base stations to differentially correct the aircraft location. But the cost of the system would go up appreciably, and the need to establish local base stations would hamper this system's use in remote, inhospitable areas.

Figure 2 presents results which compare building heights measured in the field to heights measured by the laser. Buildings were measured rather than trees because it is easier to identify and measure the top of a building (better line-of-sight, obvious surfaces) and because buildings - collections of straight lines, flat surfaces, and right angles - are much more forgiving with respect to errors in flightline location. Man-made structures ranging in height from 1.2 to 63.1 meters were measured using a handheld laser rangefinder, the Jenoptik LEDHA-GEO. The linear equation relating the laser to ground heights has a slope close to but significantly different from 1.0 at the 95 percent level of confidence ($p < 0.0001$). The mean difference between laser and ground measurements was 17 cm ± 59 cm, insignificant at the 95 percent level of confidence (two-sided paired t-test, $p = 0.0423$). Laser-ground differences ranged from −2.1 to +2.0 meters; 90 percent of the differences fell between −0.6 and +1.0 meters. It is the opinion of the primary author that much of this variability reflects a lack of precision in the ground measurements, not laser inaccuracies.

TABLE 3. BENCH TEST RESULTS FOR PALS

	stan. dev.	range
1. *GPS Location Stability*:	*(meters)*	*(meters)*
Differential: Latitude:	0.93	5.56
Longitude:	0.57	7.16
Elevation-MSL:	1.79	11.6
Non-Differential: Latitude:	1.30	9.27
Longitude:	1.43	11.46
Elevation-MSL:	2.40	16.5
2. *Range Stability* to a ~70-m target (brick wall):		
first hour: mean	70.39 m	
sd:	0.06 m	
range:	0.4 m (70.1 m to 70.5 m)	
Results duplicated in 2nd hour-long test.		
No degradation over time (5 minute intervals over hour).		
3. *Repetition rate stability* over time:		
5 minute blocks of data, e.g., 0–5 min, 15–20 min, 30–35 minutes, . . . over a two hour period.		
overall mean (2 hr):	2086.34 hz	
mean, 1st hr:	2087.00	
range, 5 min blocks, 1st hr:	2085.0 to 2087.5 hz	
mean, 2nd hr:	2085.67 hz	
range, 5 min blocks, 2nd hr:	2084.2 to 2086.7 hz	

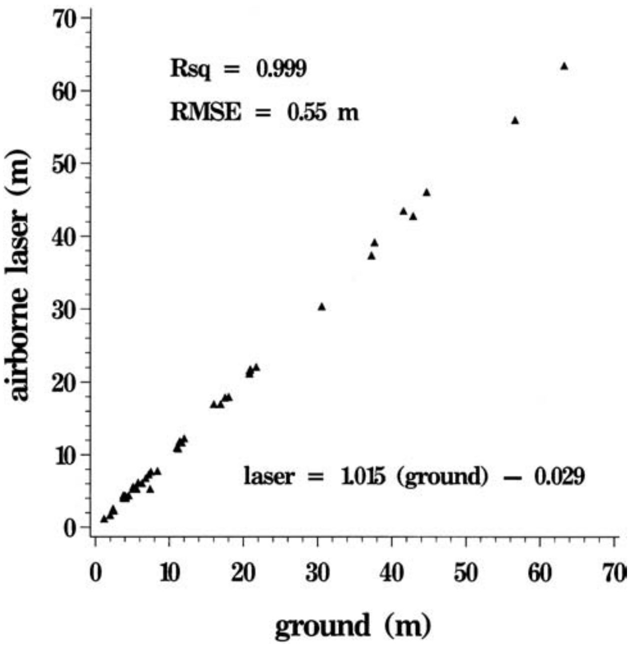

Figure 2. Relationship between ground-measured building heights and airborne laser measurements of the same buildings.

Post-Flight Processing

PALS is a first-return, airborne laser profiling system. In order to measure tree heights along these first-return transects, a ground-finding program was developed to define a ground trace beneath the forest canopy. Once this ground line was defined by identifying and interpolating between suspected ground hits, a canopy height measure could be defined for each pulse.

The frequency with which ground is found beneath a forest canopy is a function of the density of the forest, the laser spot size at target, and the sensitivity of the laser (Aldred and Bonner, 1985). The sensitivity of the PALS laser receiver cannot be adjusted in the field, and it was common to range off of power lines which undoubtedly intercepted less than 10 percent of the 0.3-m laser footprint. Although ground returns were infrequent in the typically dense, young secondary forests of Delaware, enough occurred within the stands and at field/stand edges, grade crossings, and waterways that a coherent ground trace could be fashioned.

The ground-finding program identifies local minima within a user-defined window and then fits a spline to the suspected ground hits. The window size used in Delaware was 1 or 2 seconds - 1 second in the hilly terrain of northern Delaware and 2 seconds on the flats. The analyst reviews a flightline and may adjust one or more of the minima in order to produce what he/she believes is an adequate representation of the ground. The program also interpolates, for each pulse, the GPS latitude/longitude, GMT, aircraft elevation above MSL, and the aircraft ground speed and heading. These position/time data plus the range-to-canopy, range-to-ground, and amplitude are recorded for each pulse. The file output by the ground-finding program serves as the base file in all subsequent processing involving GIS and forest inventory analyses.

Subsequent PALS-like systems will want to incorporate a laser which, at a minimum, sequentially toggles between first and last returns. The identification of a reliable ground line was straightforward in Delaware where topography is minimal and the forests are highly dissected. Establishing a reliable ground line in mountainous or jagged terrain in areas of contiguous, high-LAI forests would be problematic using a first-return laser. When the PALS components were purchased in 1999, the sequential toggling was not available; it is today. Likewise, relatively inexpensive laser scanners are also available, and one of these might be substituted for the first-return laser transmitter/receiver.

Summary

A simple, portable airborne laser profiling system has been assembled from off-the-shelf, commercially available components. The system is designed to be small, lightweight, simple, relatively inexpensive, easy-to-install, and easily operated by one person. The system is designed to be transported to remote sites and installed aboard local, for-hire aircraft. One person transports, installs, and operates the system; support staff (other than a pilot) is unnecessary.

The system was designed with economy, portability, and component availability in mind. PALS is undoubtedly one of the simplest laser profiling systems around, and it provides a relatively simple data stream of first-return measurements. It lacks the dGPS and inertial information needed (1) to accurately locate the laser trace on the ground to better than 10 meters, and (2) to accurately map topography. As such, it should be considered a tool which can be used to accurately measure relative heights, e.g., vegetation canopy heights or building heights locally (sub-meter). It is not designed to accurately measure topography relative to a fixed datum, e.g., elevation above mean sea level. In this respect, PALS gathers approximate measures, reporting heights with an accuracy above a fixed datum of 10 to 20 meters along regional profiles tens or hundreds of kilometers long. Given such characteristics, PALS can be used to measure forest heights, but should not be used to establish or validate DTMs or DEMs.

Improvements to this design are already on the shelf and should be considered for incorporation into new PALS-like instruments. Riegl, and perhaps others, currently sell lasers which sequentially toggle between measurements of first and last returns. Use of this laser would significantly facilitate ground-finding under dense canopies growing on rugged terrain. Certainly, more expensive dGPS systems are available which differentially correct on the fly without the need for base stations or U.S. Coast Guard beacons. Unfortunately, these units currently cannot leave the country, so they're ruled out if the laser might be used for work outside the U.S.A. A third improvement would be the incorporation of tiltmeter data into the laser data stream. Two-axis electronic tiltmeters accurate to tenths of a degree can be purchased for a few hundred dollars, and incorporation of pitch and roll information would further refine the ground location of the laser trace.

One problem was noted during the Delaware overflights. A few of the components reported in this configuration are unshielded, and operation of the airborne laser system did interfere with aircraft-tower communications. Although the interference could be controlled by reducing the squelch on the helicopter's radio, the squelch adjustment reduced the operating radius of the radio. Tests were run in-flight to try to identify the offending electronics, and it appears that it came from two sources. The GPS remote satellite antenna was one significant source of radio frequency noise. We recommend that a GPS avionics satellite antenna be used and located away from the aircraft radio. A second source of noise was the 18- to 36-vdc to 12-vdc converter. It is recommended that the converter be housed in a shell constructed from materials which block rf noise.

The system has limitations. PALS can effectively operate up to 300 m above terrain. Above 300 m, the laser return becomes weak enough that significant data dropout occurs, especially over forests. (Below 300 m, significant dropout is limited to areas of standing water, which absorbs the near-infrared laser pulse.) This 300-m limit makes the system ill-suited to overflights of mountainous areas in fixed-wing aircraft. If use is contemplated in areas with significant topography, then necessarily the system will have to be mounted aboard a helicopter so that the operational envelope can be maintained. The effects of aircraft speed and elevation changes necessitated by undulating topography can be removed from the laser ranging data in the data post-processing phase.

The simplicity, the compactness, and the meager power requirements of the system preclude the need for dedicated support aircraft and staff, thereby greatly reducing research or operational budgets. These cost savings will permit foresters to employ such systems in locales where reconnaissance-level forest inventory data are most needed, e.g., in understudied regions in the Amazon, the Congo, Southeast Asia, and the circumpolar boreal forests of Canada and Russia.

References

Aldred, A.H., and G.M. Bonner, 1985. *Application of Airborne Lasers to Forest Surveys*, Information Report PI-X-51, Petawawa National Forestry Institute, Canadian Forest Service, Agriculture Canada, Chalk River, Ontario, Canada, 62 p.

Arp, H., J-C. Griesach, and J.P. Burns, 1982. Mapping in tropical forests: A new approach using the laser APR, *Photogrammetric Engineering & Remote Sensing*, 48(1):91–100.

Baltsavias, E.P., 1999. Airborne laser scanning: Existing systems and firms and other resources, *ISPRS Journal of Photgrammetry and Remote Sensing*, 54:164–198.

Blair, J.B., D.B. Coyle, J.L. Bufton, and D.J. Harding, 1994. Optimization of an airborne laser altimeter for remote sensing of vegetation and tree canopies, *Proceedings, IGARSS'94*, 08–12 August, Pasadena, California, 2:939–941.

Blair, J.B., D.L. Rabine, and M.A. Hofton, 1999. The Laser Vegetation Imaging Sensor: A medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography, *ISPRS Journal of Photogrammetry and Remote Sensing*, 54:115–122.

Harding, D.L., J.B. Blair, J.G. Garvin, and W.T. Lawrence, 1994. Laser altimeter waveform measurement of vegetation canopy structure, *Proceedings, IGARSS'94*, 08–12 August, Pasadena, California, 2:1250–1253.

Hickman, G.D., and J.E. Hogg, 1969. Application of airborne pulsed laser for near shore bathymetric measurements, *Remote Sensing of Environment*, 1:47–58.

Hoge, F.E., R.N. Swift, and E.B. Frederick, 1980. Water depth measurement using an airborne pulsed neon laser system, *Applied Optics*, 19(6):871–883.

Hoge, F.E., R.N. Swift, and J.K. Yungel, 1983. Feasibility of airborne detection of laser-induced fluorescence emissions from green terrestrial plants, *Applied Optics*, 22(19):2991–3000.

Krabill, W.B., J.G. Collins, L.E. Link, R.N. Swift, and M.L. Butler, 1984. Airborne laser topographic mapping results, *Photogrammetric Engineering & Remote Sensing*, 50(6):685–694.

Lefsky, M.A., D. Harding, W.B. Cohen, G. Parker, and H.H. Shugart, 1999a. Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA, *Remote Sensing of Environment*, 67:83–98.

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

Link, L.E., and J.G. Collins, 1981. Airborne laser systems use in terrain mapping, *Proceedings, 15th International Symposium on Remote Sensing of Environment*, 11–15 May, Ann Arbor, Michigan (ERIM) 1:95–110.

Maclean, G.A., and W.B. Krabill, 1986. Gross-merchantable timber volume estimation using an airborne LIDAR system, *Canadian Journal of Remote Sensing*, 12(1):7–18.

Means, J.E., S.A. Acker, D.J. Harding, J.B. Blair, M.A. Lefsky, W.B. Cohen, M.E. Harmon, and W.A. McKee, 1999. Use of large-footprint scanning airborne lidar to estimate forest stand characteristics in the western Cascades of Oregon, *Remote Sensing of Environment*, 67:298–308.

Means, J.E., S.A. Acker, B.J. Fitt, M. Renslow, L. Emerson, and C. Hendrix, 2000. Predicting forest stand characteristics with airborne scanning lidar, *Photogrammetric Engineering & Remote Sensing*, 66(11):1367–1371.

Næsset, E., 1997a. Determination of mean tree height of forest stands using airborne laser scanner data, *ISPRS Journal of Photogrammetry and Remot Sensing*, 52(2):49–56.

———, 1997b. Estimating timber volume of forest stands using airborne laser scanner data, *Remote Sensing of Environment*, 61:246–253.

Nelson, R., 1997. Modeling forest canopy heights: The effects of canopy shape, *Remote Sensing of Environment*, 60:327–334.

Nelson, R., W. Krabill, and J. Tonelli, 1988a. Estimating forest biomass and volume using airborne laser data, *Remote Sensing of Environment*, 24:247–267.

Nelson, R., R. Swift, and W. Krabill, 1988b. Using airborne lasers to estimate forest canopy and stand characteristics, *Journal of Forestry*, 86(10):31–38.

Nelson, R., R. Oderwald, and T.G. Gregoire, 1997. Separating the ground and airborne laser sampling phases to estimate tropical forest basal area, volume, and biomass, *Remote Sensing of Environment*, 60:311–326.

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

Popescu, S., R.H. Wynne, and R.F. Nelson, 2000. Estimating forest vegetation biomass using airborne lidar measurements, *Proceedings, 2nd International Conference - Geospatial Information in Agriculture and Forestry*, 10-12 January, Lake Buena Vista, Florida (ERIM), 2:346–353.

———, 2002. Estimating plot-level tree heights with lidar: Local filtering with a canopy-height based variable window size, *Computers and Electronics in Agriculture*, accepted for publication.

Ritchie, J.C., J.H. Everitt, D.E. Escobar, T.J. Jackson, and M.R. Davis, 1992. Airborne laser measurements of rangeland canopy cover and distribution, *Journal of Range Management*, 45(2):189–193.

Ritchie, J.C., D.L. Evans, D. Jacobs, J.H. Everitt, and M.A. Weltz, 1993. Measuring canopy structure with an airborne laser altimeter, *Transactions of the American Society of Agricultural Engineers*, 36(4):1235–1238.

Schreier, H., J. Lougheed, C. Tucker, and D. Leckie, 1985. Automated measurements of terrain reflection and height variations using an airborne infrared laser system, *International Journal of Remote Sensing*, 6(1):101–113.

(Received 21 November 2001; revised and accepted 14 June 2002)