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A.H. Aldred and G.M. Bonnor

Information Report PI-X-51
Petawawa National Forestry Institute

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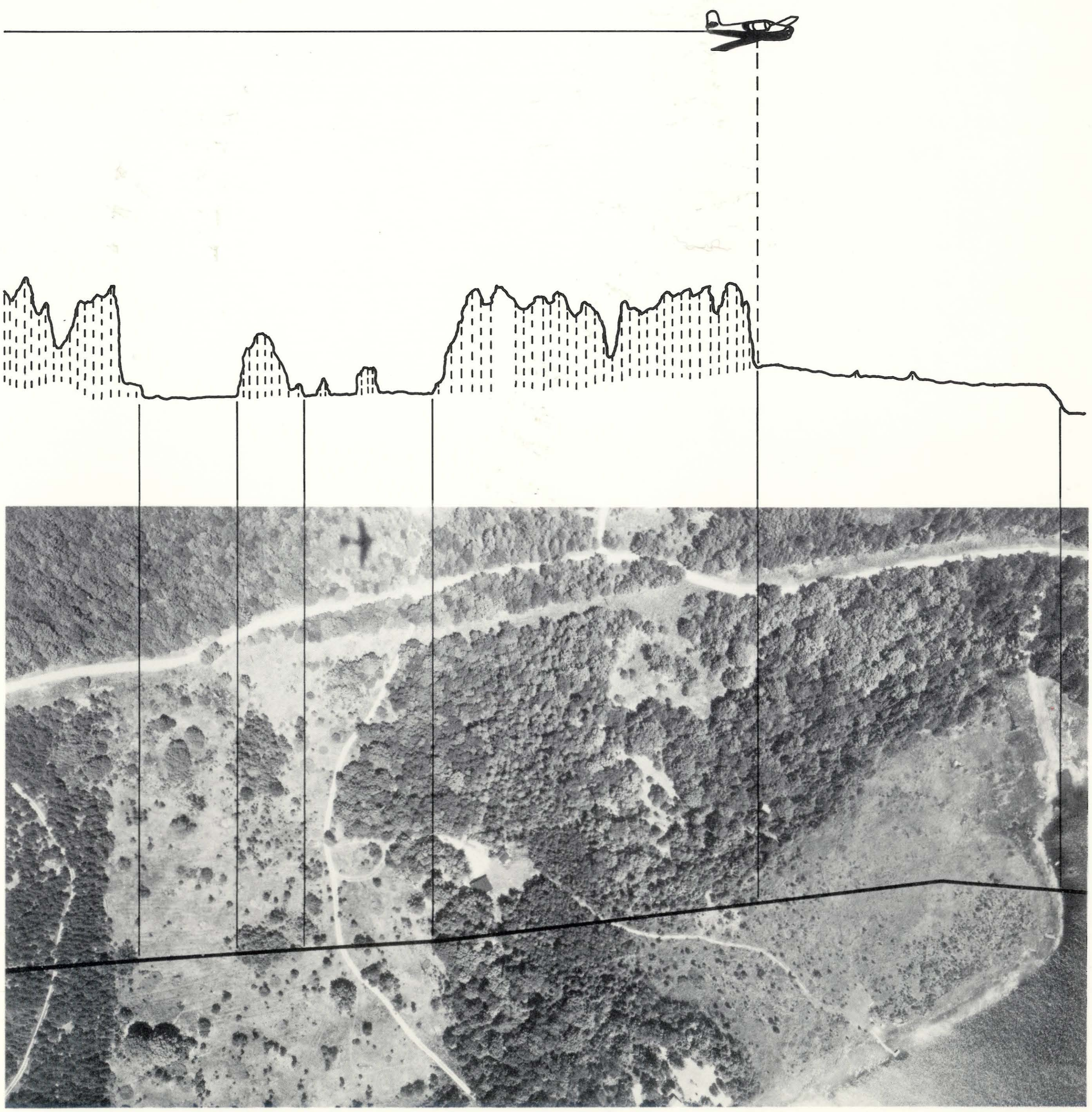

APPLICATIONS OF AIRBORNE LASERS TO FOREST SURVEYS

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aux inventaires forestiers.**

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ABSTRACT

The purpose of the project was to determine what information of significance to forest surveys could be obtained from recent advances in pulsed laser technology. The project involved four phases: 1) the preliminary investigation of pulsed laser waveforms (return pulses) as influenced by the forest and other terrain features, 2) development of hypotheses and procedures for the extraction of forest stand information from laser data, 3) a formal test of hypotheses concerning the use of pulsed lasers to produce forest survey information, and 4) the assessment of applications and benefits.

The results of the investigation of basic properties of pulsed laser returns, informal and formal statistical tests, conclusions, and recommendations on the direction of further work are reported. Particularly promising results were obtained using pulsed lasers to estimate heights and densities of forest stands, and in the potential of using pulsed lasers for forest and terrain profiling.

RÉSUMÉ

L'objet des travaux était de déterminer la nature des renseignements utiles aux inventaires des forêts qu'on pouvait obtenir grâce aux derniers perfectionnements des techniques du laser impulsionnel. Ces travaux comptaient quatre étapes: (1) l'étude préliminaire des formes d'ondes (réfléchies) du laser impulsionnel, sous l'effet des éléments remarquables du terrain et du couvert forestier; (2) l'élaboration d'hypothèses et de procédés en vue d'extraire des renseignements sur les peuplements à partir des données lasers; (3) une vérification formelle des hypothèses construites sur l'inventaire des forêts au moyen des lasers impulsionnels; et (4) l'évaluation des applications et des avantages.

Les résultats de l'étude des propriétés fondamentales des signaux réfléchis, les tests statistiques, formels ou non, les conclusions et les recommandations pour orienter les travaux à venir sont tous signalés. Le laser impulsionnel a eu des résultats particulièrement prometteurs pour ce qui est d'estimer la hauteur et la densité des arbres dans les peuplements. Quant aux possibilités de profilographie des forêts et du terrain, elles sont remarquables.

A.H. Aldred is Vice-President of Dendron Resource Surveys Ltd., Ottawa, and G.M. Bonnor a Research Scientist at the Petawawa National Forestry Institute.

ADVANCED AIRBORNE SYSTEMS
FOR FOREST SURVEYS

INTRODUCTION

Distinct shortages of mature timber are apparent in most regions of Canada. The shortfalls make it imperative that the resource be better managed and more intensively utilized. This need, in turn, demands improved information on the amount of resource available, and the dynamic elements of regeneration, growth, and depletions. The shortages are also forcing harvesting and management activities into less accessible forests where all practices, including the collection of information, are much more expensive. The forest manager, as a consequence, is constantly on the lookout for faster and cheaper means of collecting resource information. Developments in aerial photography and remote sensing in the past have proved useful in this respect, the degree of payoff being tied to how inaccessible or remote the resource is.

The purpose of this project was to investigate the opportunities offered by recent technological advances in airborne sensing and survey methods. It was based directly on recent past projects of the Canada Centre for Remote Sensing (CCRS) to develop a lidar system for bathymetry, and on CCRS research into inertial navigation systems. Specifically, this project concentrated on the investigation of properties of pulsed laser signals reflected from forest vegetation and associated terrain. The objectives were to find a more efficient means of collecting and processing information normally obtained through forest survey, and to explore the possibilities of producing new information of value in forest management.

Towards these ends, the project began with the investigation of the basic properties of pulsed laser waveforms reflected from forest vegetation and other targets. This information established a foundation for the development of specifications and procedures for acquiring the laser data, and eventually producing the needed forestry information. The developed theories were then tested, first informally to look for improvements and refinements, and then formally so that the theories could be rigorously tested and the procedures evaluated. Finally, conclusions were drawn on the performance of the laser sensors over forested terrain, recommendations made for the optimization of such sensors, and advice offered to resource managers on the practical value of laser sensors in the field of forestry. Following this general approach the project was conducted according to four phases:

- Phase I: Preliminary investigation of pulsed laser waveforms as influenced by the forest and other terrain characteristics.
- Phase II: Development of theories concerning the extraction of forest survey information from laser data.
- Phase III: Formal test of hypotheses concerning the use of laser data to produce forest survey information.
- Phase IV: Applications and benefits.

BACKGROUND

During the last 15 years, many technological advances have been made in avionics and the development of airborne sensors. Radar and laser distance measurement devices, often used as profilometers, are among those of particular interest in the forest survey area. Their role has taken two general forms: 1) use of distance data to aid in the control of other sensors, and 2) extraction of useful resource information directly from returned signatures. An example of the former is the use of airborne profile recorders (APR) based on radar to provide auxiliary control data for photogrammetric models or triangulation networks. The latter is well exemplified by the use of vertical profiles to characterize sea ice, terrain features, or forest stands.

In the case of topographic mapping applications, however, the forest cover frequently has posed a serious impediment to accurate terrain profiling because of the failure of the energy to penetrate to the ground beneath the tree canopy. Radar altimeters, used as aids to aircraft landing, in fact were specifically designed to register on the tops of trees for obvious reasons. In the forestry case, where the trees are the primary target, readings of both the vertical location of the terrain and the canopy together are important sometimes referred to as a double return or trace (Figure 1). Such double returns provide valuable information on stand height, crown cover density, and perhaps species composition directly, and volume and biomass indirectly through correlation with height, density, and other data. This information is fundamental to forest surveys and is currently obtained through labour intensive and demanding manual photo interpretation and field procedures. Stand height, so basic to a forest survey, is often impossible to obtain through radar in tropical forests, and at the medium scales usually used for photo interpretation, not very accurate even for temperate forests. Estimates within ± 5 to 8 m are considered satisfactory (Nielsen 1971).

In the early 1960s, airborne profile recorders based on radar altimeters were being developed to provide vertical control data for medium and small scale mapping. At about the same time, the use of low altitude aerial photographs for tree measurements was developing. This necessitated some means of measuring the distance from aircraft to ground at the time of exposure. Distance was needed to determine the scale of the photogrammetric model used to measure several tree dimensions (e.g., height, volume, and biomass). Twin cameras on a base of known length, radar altimeters, and laser ranging devices were the options considered. More or less simultaneously, the two-camera approach was successfully adapted to helicopter use in British Columbia (Lyons 1967) and a low-altitude, vegetation-penetrating radar altimeter was developed by the National Research Council (NRC) for the Canadian Forestry Service (Aldred and Sayn-Wittgenstein 1968a, Neilsen 1970) and later manufactured. At that time, lasers were heavy and required considerable power to operate, but the NRC predicted that lasers would ultimately provide the best solution to forestry applications, as the technology developed and instruments became smaller, lighter, and perhaps cheaper.

The production model low altitude radar altimeter usually met the accuracy requirement (± 2 per cent of flying height at 95 per cent level) under Canadian conditions and was found to successfully penetrate northern

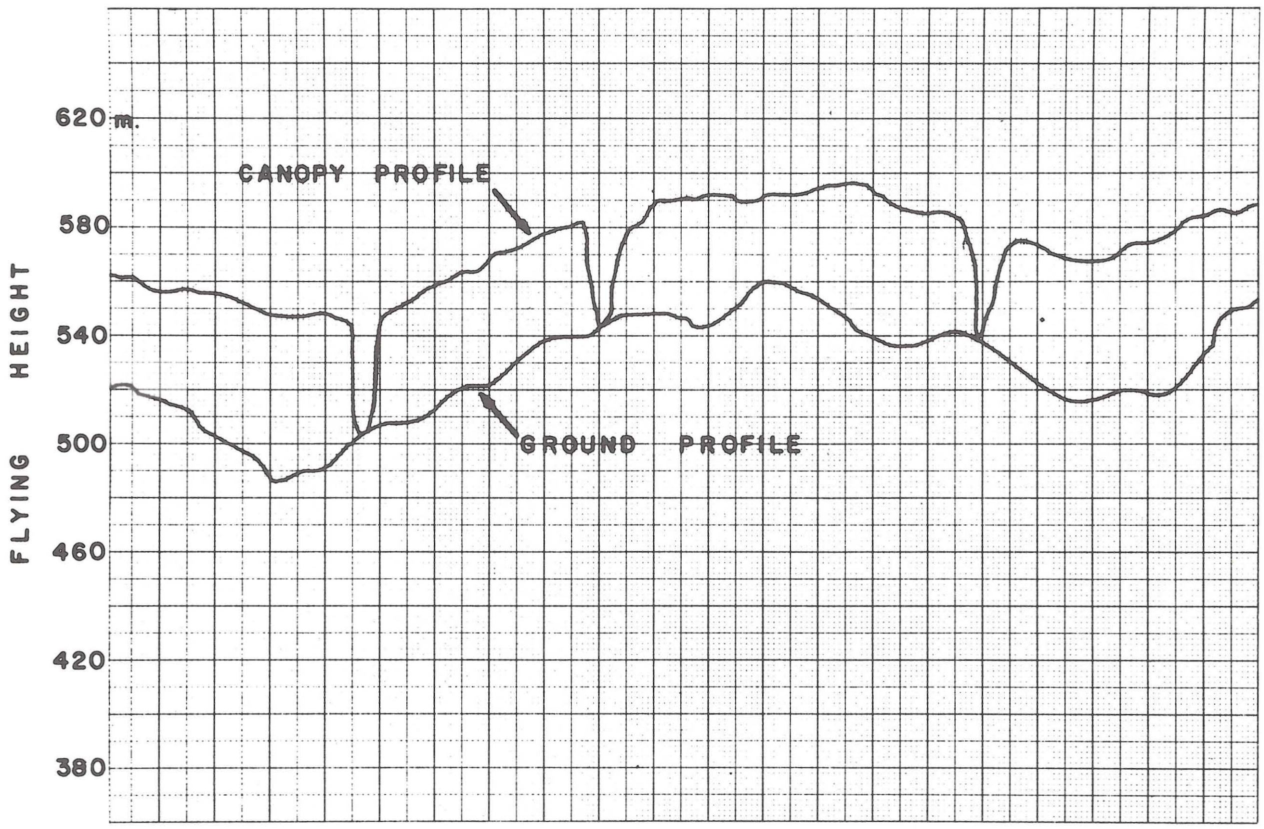


Figure 1. Diagram of a double trace showing profiles of both the forest canopy and underlying terrain.

temperate forest stand canopies (Nielsen 1974). The radar altimeter was first tested under tropical forest conditions in Guatemala, where trouble was encountered in penetrating the vegetation (Sayn-Wittgenstein and Aldred 1968b). Two further attempts were made in Surinam and Costa Rica to overcome the deficiency (Nielsen 1974b, Nielsen and Aldred 1978). Difficulty was experienced in obtaining consistent results partly because the radar was based on aging technology which tended to be unstable. The possibility of obtaining a double trace of both the canopy and ground was explored in Costa Rica, but the accuracy of tree profiles was not established. The altimeter was subject to deviations caused by sampling and data integration procedures and by the effect of relatively open crowns which did not always provide a sufficiently solid radar energy reflector (Nielsen and Aldred 1973).

By the mid 1960s, laser distance-measurement devices adapted to airborne operation were being explored (Rempel and Parker 1964, Jensen and Ruddock 1965, Jensen 1967). The adaptation involved the use of powerful lasers which would respond to laser energy reflected from natural surfaces, rather than from mirrors or retroreflectors normally used during ground-based distance measurement. The airborne adaptation also involved vertical mounting of a laser and use of chart recorders to handle the large volumes of data generated during the flight. Another early description of such a system used for terrain profiling was provided by Schweider (1969). The U.S. Army also conducted an exhaustive study of the properties of the same Spectra-Physics helium/neon gas laser based on continuous wave (CW) phase shift measurement principles (Link 1973). The objective of the U.S. Army study was to determine the feasibility of using a laser profilometer to rapidly appraise terrain slope, roughness, and presence of obstacles on selected, unprepared landing sites. Several authors have written on the use of airborne CW laser profilometers for sea ice profiling, including Hibler (1975), Tooma and Tucker (1973), and Kirby and Sutton (1981). Figure 2 illustrates a profile produced by a CW laser.

Other applications of CW laser profilometers have been described covering terrain features such as microrelief, hydrographic features, open ground, grass cover, corn crops, plowed fields, trees, etc. (Rempel and Parker 1964, Link 1969). The Canadian Forestry Service tested a similar CW helium-neon gas laser in 1973 to explore forestry potential (Forest Mgmt. Inst. 1978). The distance measurement was tested both on ground and from the air. Measurement accuracy (better than ± 30 cm and 300 m) was found to exceed the forestry requirement, but the penetration of the forest canopy to ground level occurred only at definite crown openings. Therefore, stretches of several hundred metres could occur without a ground level sample. In hilly terrain the ground elevation, and thus the stand height, could only be vaguely estimated. Some applications of laser profilometers involving tropical forest conditions were described by Arp et al. (1982) using a CW laser. The focus was on the collection of terrain elevation data, the forest being chiefly an obstacle to work around. Obtaining a sufficient number of laser readings which penetrated to ground level remained a major drawback. The dense, multi-storied tropical stands afforded even fewer "holes" in the canopy than temperate forest.

Pulsed lasers were developed for airborne operation during the mid- and later 1970s. Pulsed techniques were attractive because of the simplicity of the distance measurement principle: it was based on the propagation time for a light pulse to travel from source to target and back to the receiver. Given the velocity of light, the measured lapse time can be converted to distance. Using short pulses and signal processing techniques, distance measurement accuracies can approach several centimeters. The use of a pulsed laser as a profilometer is illustrated in Figure 3. The approach has been well described by Mamon et al. (1976, 1978). Successful applications of pulsed lasers in the ice reconnaissance field have been reported by Fabian et al. (1979) and Lowry and Brochu (1975); in the hydrography field (especially water depth) by O'Neil (1980), Hodg et al. (1980), and Enabnit (1979); and in the area of topographic mapping, microrelief, and terrain trafficability by Collins (1979), Krabill et al. (1981), and Link and Collins (1981). The last authors also touched on crops and the problems posed by forest cover, as did Nelson et al. (1983). Krabill et al. (1984) tested the application of an oceanographic lidar, originally developed for bathymetric work, as a terrain profiler. The investigation was particularly relevant because the authors attempted to cope with the effect of forest cover. They found that under winter (leaf-off) conditions, about 40 percent of the pulses penetrated to the ground surface, making terrain profiling fairly reliable. However, under summer (leaf-on) conditions, the penetration was much less reliable. The penetration of coniferous stands was found to be better than of deciduous stands in the summer but, because the test area included little coniferous cover, no firm conclusions could be reached. Undercover vegetation was also found to have a significant effect on penetration. Krabill et al. (1984) concluded by suggesting that a high laser-pulse repetition rate at low altitude with a very narrow beam width may achieve better penetration and should be tested.

The latest development in pulsed lasers concerns the airborne or spaceborne use of laser scanners which sample vast quantities of range data repeatedly along scan lines running transverse to the flight path (Krobick and Elacki 1981) or in some elliptical pattern. Krabill et al. (1984) also refer to the use of conical scanners which will sample swaths rather than transects. The Canada Centre for Remote Sensing is currently developing a scanning laser for bathymetric work which should be ready for testing in the fall of 1984. In the future these advances may have an important role to play in forestry surveys. The present project, however, confined itself to the basic properties of laser pulses reflected from forest vegetation. Hopefully, the research may pave the way to forestry applications of the rapidly evolving technology.

MATERIALS AND METHODS

The basic operating principles of the lasers involved are outlined briefly, followed by a description of two laser systems used in the project. The data processing components are described, as well as the airborne systems. Finally, the sites where airborne trials were conducted are described.

Principle of operation

The operating principle behind a ranging (distance measurement) pulsed laser is simple. A short-duration (e.g. 5 to 10 ns) laser pulse is generated which is transmitted as a relatively narrow beam from the instrument towards a target. The pulse is reflected from the target and returns as an echo which is detected by a receiver. The lapse time between the initial pulse and the return is measured and converted to distance using the known velocity of light. Since light travels at about 300 x 10^3 km/s, the time measurements

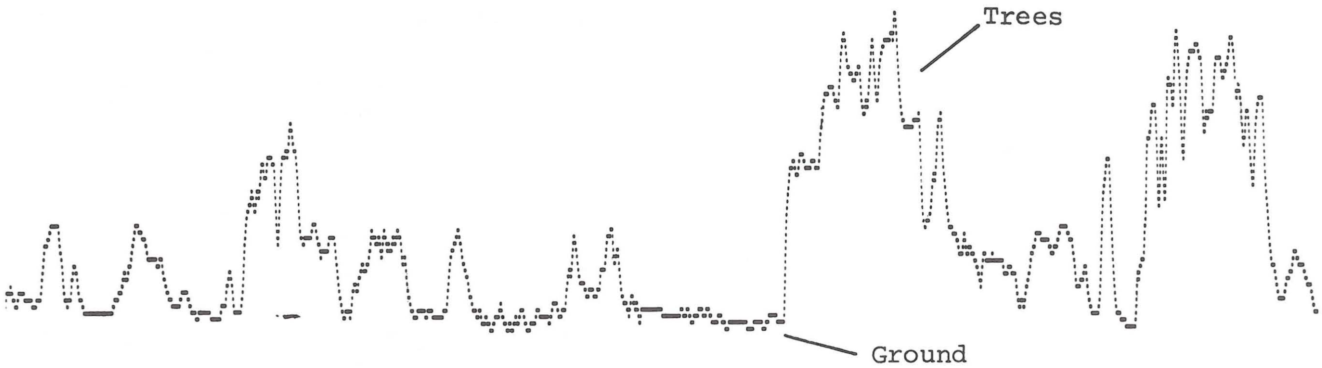


Figure 2. Example of a stripchart record of distance data from a continuous wave laser profilometer showing mixed hardwood/softwood forest cover and terrain.

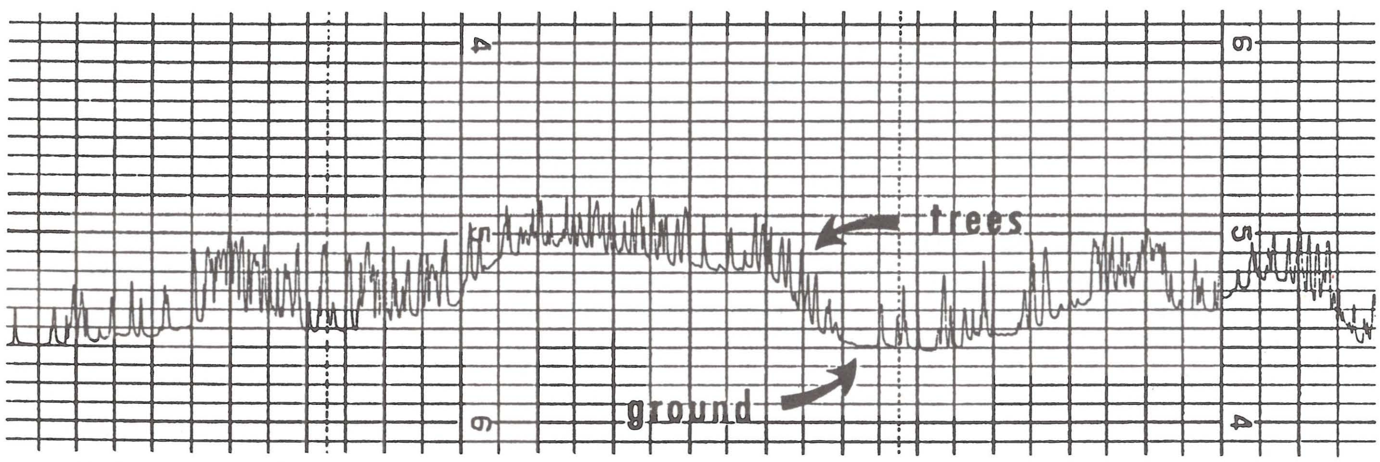


Figure 3. Example of output from a pulsed laser profilometer showing coniferous forest cover and underlying terrain.

must be in the nanosecond range; 1 ns is equivalent to about 30 cm distance. Figure 4 illustrates the principle. The better a distinct point on the transmitted and received pulse (such as the peak) can be discriminated, the more accurate the measurement of distance.

The two lasers tested in this project were both capable of range measurement. However, the CCRS bathymetric laser was developed so that the wave-form of the return pulse could be captured. That is, both the transmitted and returned peak pulse time and the varying amplitude of the entire echo are coded (Figure 5). The original purpose was to be able to detect pulse returns from both the surface of a body of water and the bottom. The differing return times could be used to determine water depth. The multiple returns from targets of different distances suggested that other targets, such as the forest canopy and terrain beneath, when viewed from above, might provide useful data on forest stand heights. This was the seed from which this project grew.

Airborne system

The systems tested in this project were an experimental bathymetric laser operated by CCRS and a smaller, production ranging laser used primarily to determine the flying height of an aircraft above ground. The former was chosen primarily for its ability to capture the returned energy waveform using a transient digitizer and high-capacity tape recorder. The latter was chosen because of availability and its fast cycling rate, the advantage of which was suggested by Krabill (1984) as a promising area of investigation.

The CCRS airborne system consisted of the following components:

MKII lidar bathymeter
Wild RC10 cartographic camera
Video camera
Inertial navigation system
Tektronix R7912 transient digitizer
Data acquisition system

The MKII lidar bathymeter has been described in detail by O'Neil (1980). The lidar has the following basic operating characteristics relevant to the forest application:

Wavelength :	1064 nm (infrared) 532 nm (green)
Pulse repetition frequency:	10 Hz
Pulse width (duration) :	5 ns at 532 nm
Maximum range :	2000 m
Beam divergence :	1,2,5,10,25 mR (selectable)

Two kinds of data were collected: distance measurements (slant range) from the infrared laser, and the amplitude of individual pulse reflections from the green laser captured with a transient digitizer. The airborne data acquisition system' accepts data from both sources, time-codes the events, and records data on computer compatible tape.

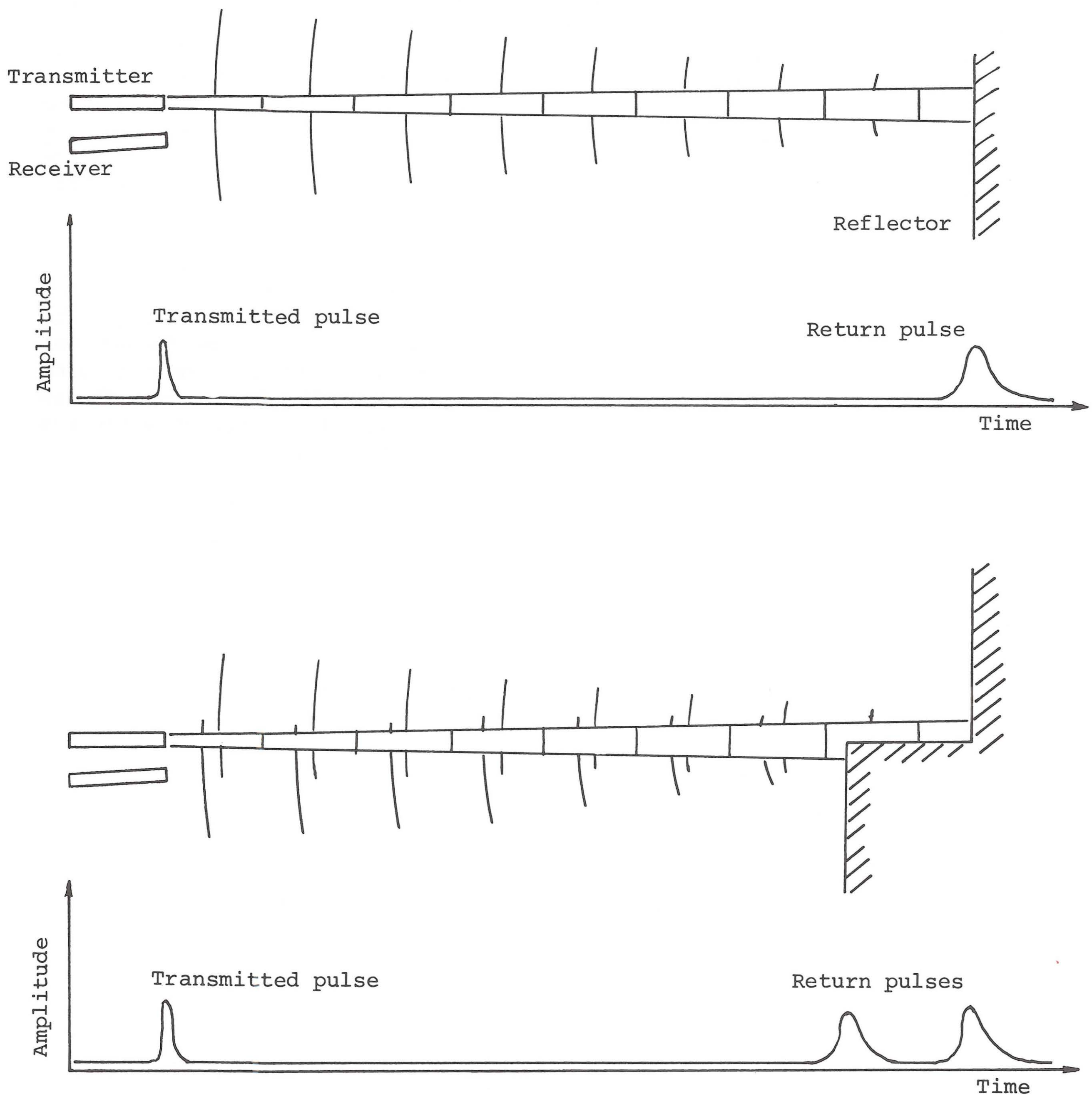


Figure 4. Diagram of timed events involved in transmitting and detecting a laser pulse; the reflection of energy from a single flat surface (above), and from a target comprised of two distances (below).

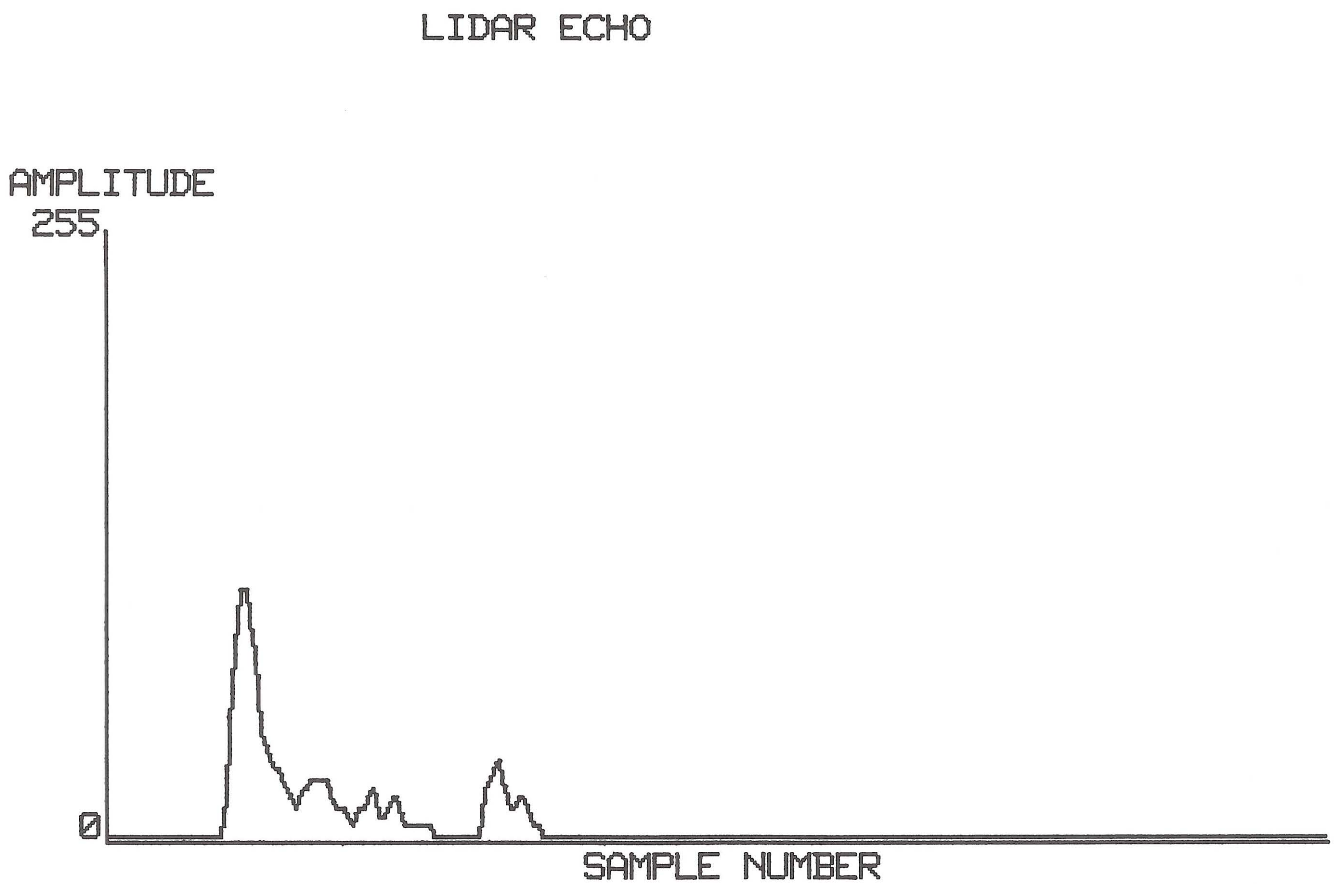


Figure 5. Example of a pulse return from forest cover, captured on a lidar bathymeter operated by the Canada Centre for Remote Sensing. The y-axis represents the strength of the returned signal and the x-axis the time duration. The earliest (leftmost) portion of the signal comes from the nearest target, here the forest canopy, and the latest from the most distant target, the forest floor or ground in this case.

The film and video cameras were used to recover the position of the flight path and the position of laser shots along the path. The procedure is detailed later in the report. The navigation data were not used because of a reduction in the scope of the project due to budget cutbacks.

The airborne system supporting the production laser consisted of:

Vinten 70 mm reconnaissance camera
Pitch and roll sensor
Barometric pressure sensor
Stripchart recorder
Digital tape recorder
Microprocessor-driven controller/data acquisition system

The production laser rangefinder had the following operating parameters:

Wavelength of laser	:	near infrared (nd-YAG)
Measurement rate	:	5,20,80,320 Hz (selectable)
Maximum range	:	500 m
Beam divergence	:	2 mR
Accuracy	:	± 40 cm

The 70 mm photos were used to complete the recovery of the flight path, analogous to the method of using the video camera referred to earlier. The pitch and roll sensor was used to correct the laser slant distance to vertical distance and to restitute photogrammetric models. The barometric sensor was used for terrain profiling applications in conjunction with the laser range-finder and pitch and roll sensor.

Lidar echo processing system (LEPS)
The CCRS lidar echo processing system is based around a PDP 11/23 computer with the following configuration: LSI 11/23 CPU, up to 256 K bytes of ram (with memory management). The peripherals interfaced to the system are a 1600 bpi tape drive, a 60 megabyte hard disk (partitioned into three volumes), a Tektronix 4025 graphics terminal and a Versatec printer/plotter.

LEPS is designed to read and process lidar recordings from the bottom echo recording system. The bottom echo recording system acquires lidar data on a CCT in a format similar to all non-imagery data collected by CCRS. Software is used to read and re-format the CCT data into disk files which allow random access to individual records in Fortran. The disk files are backed up on CCTs to eliminate the lengthy time required to strip the raw data, in case further processing is required.

LEPS contains an extensive software package called "BEST". BEST's primary role is to allow those that are not computer experts to process and manipulate lidar data through a menu system.

BEST allows graphical representations of collected data to be viewed on a Tektronix terminal or as hardcopy from the Versatec. Figure 5 illustrates a hardcopy of a pulse return; Figure 6 a number of pulse returns. The graphical features were extensively used to determine the location of prominent geographic features in the data. These points were then used to divide the data into sample subsets. The ability of the software to plot individual

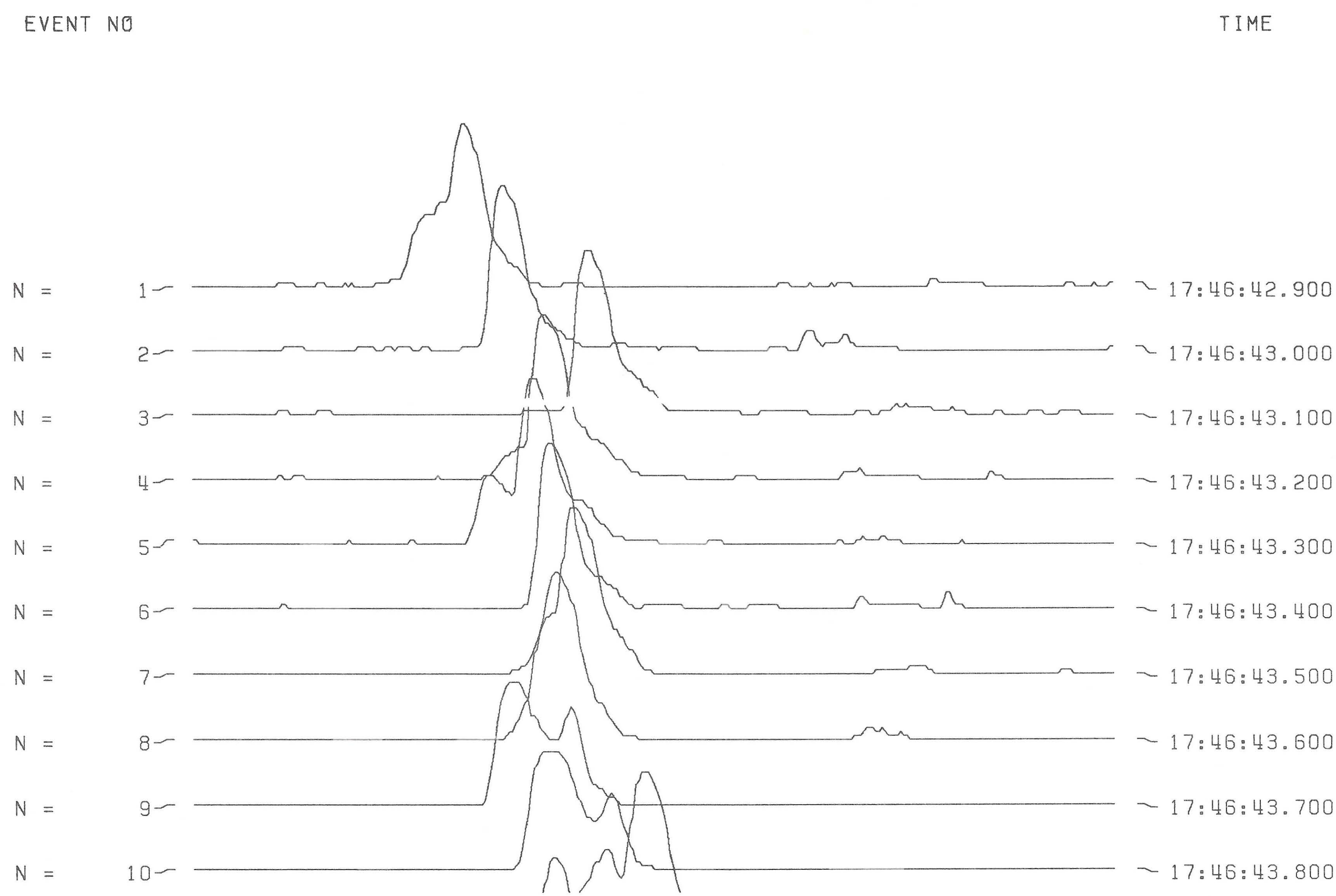


Figure 6. Example of a series of 10 laser shots captured at 1/10-second intervals.

laser returns was used to determine what effect changes in parameters such as beam divergence, stand height, and stand density had on pulse shape and magnitude.

Tree analysis software was inserted into the BEST package to simplify operator procedures and to effectively utilize common menus and subroutines. This software primarily generated numeric values for stand height, density, and species type with accompanying statistics. Graphical output was confined to data tables and stand and terrain profiles, which were used to evaluate laser profiling capabilities.

Flight line recovery

The echo recording system incorporated a video camera and recorder and a large format mapping camera. Flight line recovery was done on a video recorder with variable playback speed and freeze-frame capability.

A night flight was used to align the laser beam to the video tape. This was done by firing the laser while the video system was on. The ambient light was so weak that the video system recorded the location of the laser beam path in relation to video camera as a light flash. For flight line recovery purposes flash location was marked on the video screen to locate the laser footprint.

The video tape frames were annotated with a general header and the time of exposure to the nearest tenth of a second. The time of laser firings were also stored for each record stored on the CCT. The comparison of time on the video corresponding to a feature can then be correlated to a laser event. However, a time synchronization problem between the video and laser records was present in the airborne system, and some interpretation of pulse plots was required to pinpoint the exact laser event which correlated with a video feature.

Production laser rangefinder system

During the operation of the production system, the following data were recorded on tape: camera annotations (roll and frame number), pitch and roll attitude, atmospheric pressure, and the laser readings of distance from the aircraft to the target (usually the forest canopy or other terrain features). A microprocessor controller fired the cameras at a preselected interval and sampled data from all of the sensors at another preselected rate; this rate can be coincident or not with the camera interval. Data were placed into a buffer and delivered to the tape recorder as the camera and sampling counters advanced to the next frame and number respectively.

The data were read from the tape cassette drive with an HP micro processor and reformatted and stored in HP data files for later analysis. The analysis was carried out on the microcomputer aided by several peripheral devices such as a xy digitizer, graphics plotter, and printer. A digitized photogrammetric plotter was also used with the microprocessor to collect test data and other supplementary information.

Description of test areas

Airborne laser data covering the forest, related features, and terrain were required for all phases of the project: investigation of properties of the basic laser energy reflections from these features, development of hypotheses concerning methods of obtaining useful information and, finally, the formal testing and evaluations of the methods. The CCRS system was tested on three sites in the vicinity of Ottawa and the smaller, production laser belonging to Dendron was tested on a fourth site in western Ontario. The sites were selected to suit the requirements of the main phases of the project and to provide a reasonably broad representation of four forest cover types, flat and sloping topography, and winter versus summer season. The last mentioned concerned mainly tests of the effect of the presence or absence of hardwood leaves.

The four test sites chosen were:

1. Woodroffe Avenue site: The test area was selected in the immediate vicinity of Ottawa to cover pure and distinct stands of hardwood and softwood on flat terrain. The stands were in most cases surrounded by fields and other open ground. The test area included streets, buildings of varying size, scattered trees, and other targets of interest to the study.
2. Casselman site: This area, about 50 km east of Ottawa, was intended to cover mixed stands and a greater variety of stand heights and densities than Area 1. The topography was essentially flat, except for some abrupt elevation changes along water courses.
3. Clayton Lake site: Located about 65 km southwest of Ottawa, the test area was selected to include combinations of softwood, hardwood, and mixed stands on terrain with significant topographic relief. Some slopes were about 25 percent. A fairly wide range of stand heights and densities was available, as well as other natural targets such as open patches of grassland, rock outcrops, marshes, and swamps. The area was sufficiently unpopulated that the higher intensity laser energy settings of the CCRS laser (related to narrower beam divergence) could be tested.
4. Red Rock, Ontario site: The production system was tested during an operational project. This covered a full range of forest conditions on areas with significant topography. The tests also include coverage of a large, flat parking lot which was used to calibrate and test the accuracy of the distance measurement capabilities of the system over open ground.

It was originally intended that tests of the CCRS system be carried out twice in autumn 1982, before and after leaf fall, prior to snow accumulation. Unfortunately, the lidar system was not available in time for the "leaf on" trials. The flight was deferred until the summer of 1983. Both flights covered the same test areas although the transects did not, in most cases, coincide exactly.

Phase 1

PRELIMINARY INVESTIGATION OF PULSED LASER DATA

There are two fundamental questions concerning the use of airborne profilers to collect forest stand data. Firstly, how accurately can distance be measured from a moving aircraft? Secondly, how completely can the forest canopy be penetrated to obtain distance measurements to the ground beneath? The answers will go a long way toward determining the practical value of pulsed laser technology in providing useful forest stand height and density information --- basic to forest survey. The idealized example in Figure 7 illustrated how the penetration of the stands enables the average height of the stands to be estimated. The two questions were accordingly kept in the immediate background during the preliminary evaluation of the possibilities and in choosing the most promising directions for further work.

The purpose of Phase 1 was to review relevant past work to identify the most promising avenues, and to test available new technology on forested areas to gain a feel for the potential of pulsed lasers. The results lead up to the development of approaches, methods, and hypotheses for the later phases of work.

Objectives

The following were pursued in Phase 1:

1. The accuracy with which distance can be measured by laser from a moving aircraft to a ground target.
2. The feasibility of obtaining forest stand heights from distance measurements directly.
3. The possibility of obtaining forest stand heights from individual pulse reflections.
4. The feasibility of obtaining forest stand height data from a rapidly pulsed laser at low altitude (penetration of crown openings).
5. The degree to which the presence or absence of hardwood leaf cover influences stand height determination.
6. The effect of selectable operating characteristics of the lasers, such as beam divergence, upon stand height determination.

Procedure

After a review of past work both lasers used in this project were tested using clear, flat, surfaces such as fields and shopping centre parking lots. Flights over forest cover on test sites 1 and 4 raised the possibility of extracting stand heights directly from range data.

The analysis of the information content of individual laser pulse returns (waveforms) was based only on test flights of the CCRS laser over sites 1, 2, and 3 described earlier. These flights also enabled several beam divergence settings to be investigated. Since the first flights of the CCRS laser were done after the hardwood leaves had fallen, only the leafless condition was investigated at this time. The rangefinder laser was also flown over site 4 during leafless conditions and on an earlier occasion over hardwoods with leaves. The latter test was not designed for this project but, nevertheless, enabled some investigation of the effect of leafed hardwoods.

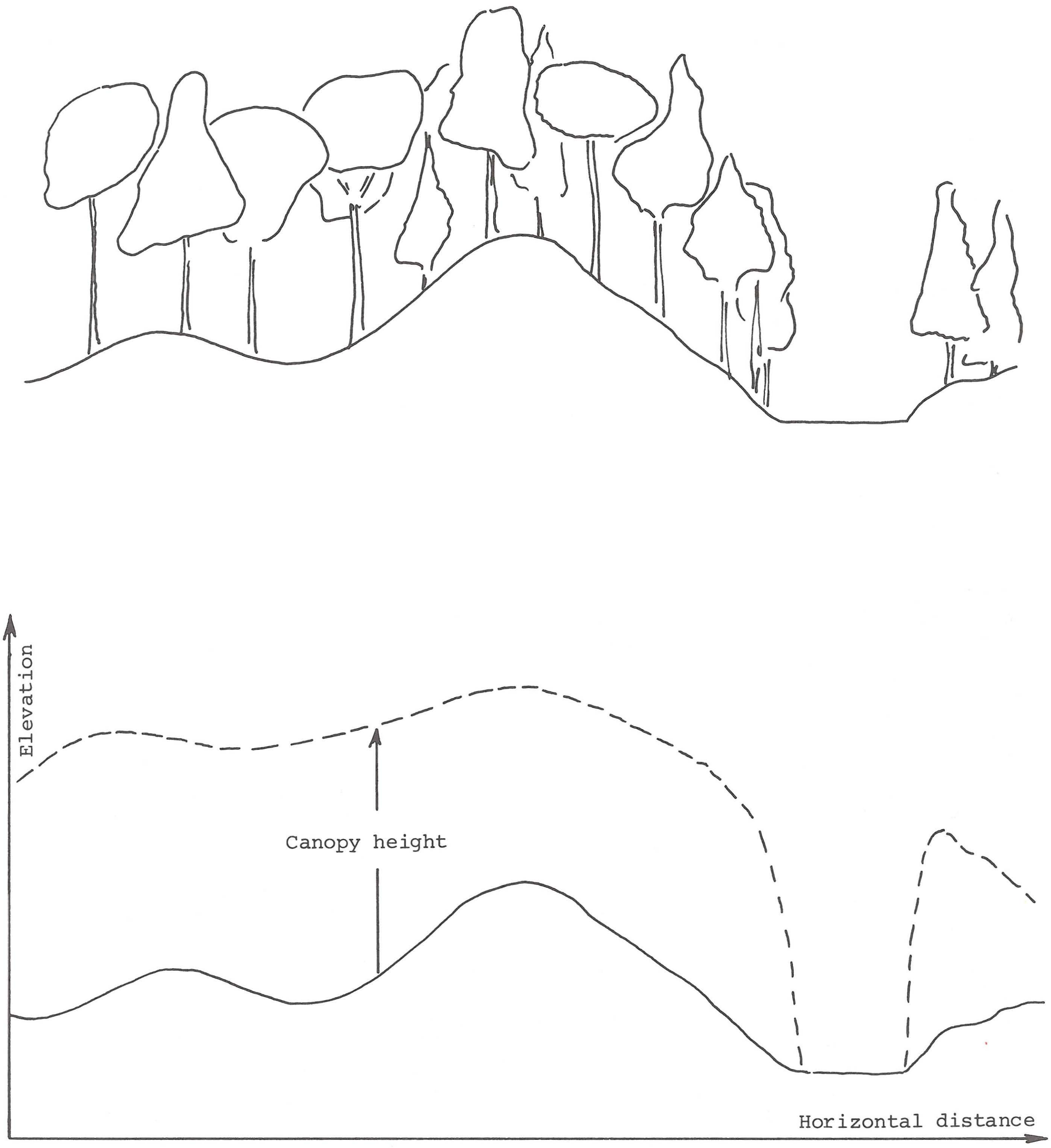


Figure 7. Cross-section of a forest stand (above) and an idealized double profile of the forest canopy and terrain, illustrating the determination of stand height.

Test flights

The flights over the three local areas (sites 1 to 3) described earlier were completed with the CCRS system on December 13, 1982. Site 4 was flown on October 28-30, 1982 with the production laser. Data from navigation sensors on the CCRS mission were recorded on the airborne data acquisition system (ADAS) and the laser and time-code data on the bathymetric data acquisition system. The production laser data were captured on film, a cassette tape recorder, and stripchart recorder. The alignment of photo and video cameras with the CCRS laser (bore sighting) was completed during a second, night flight just after the main mission. The bore sighting of the production system was completed using an infrared viewer and alignment in the laboratory.

Data handling

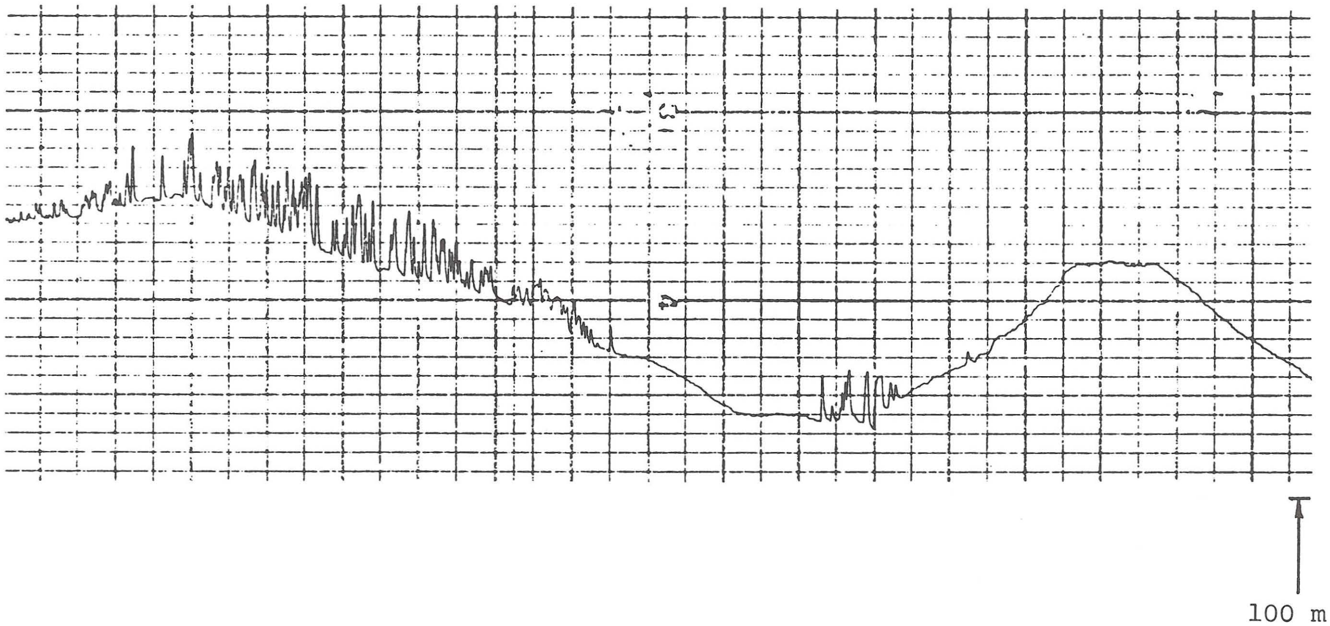
The CCRS films were processed, annotated, and printed following the flight. The data recorded by the bathymetric data acquisition system were transferred to the CCRS laser data processing computer, reformatted, and placed on temporary disk storage. Available software was used to extract both the range data (distances) and data pertaining to individual pulse reflections or echoes. Much of the data were examined on a video monitor and the most relevant examples were plotted for further analysis. For tests of particular forest stands, series of echoes were plotted (Figure 6).

Data from the production laser consisted primarily of continuous strip chart records of aircraft-to-target distance. The camera exposures were also recorded as event marks on the edge of the chart (Figure 8). When the photo mission was completed, the films were processed, annotated, and the flight path recovered. The correspondence of photos with strip chart events was established and the latter hand-annotated.

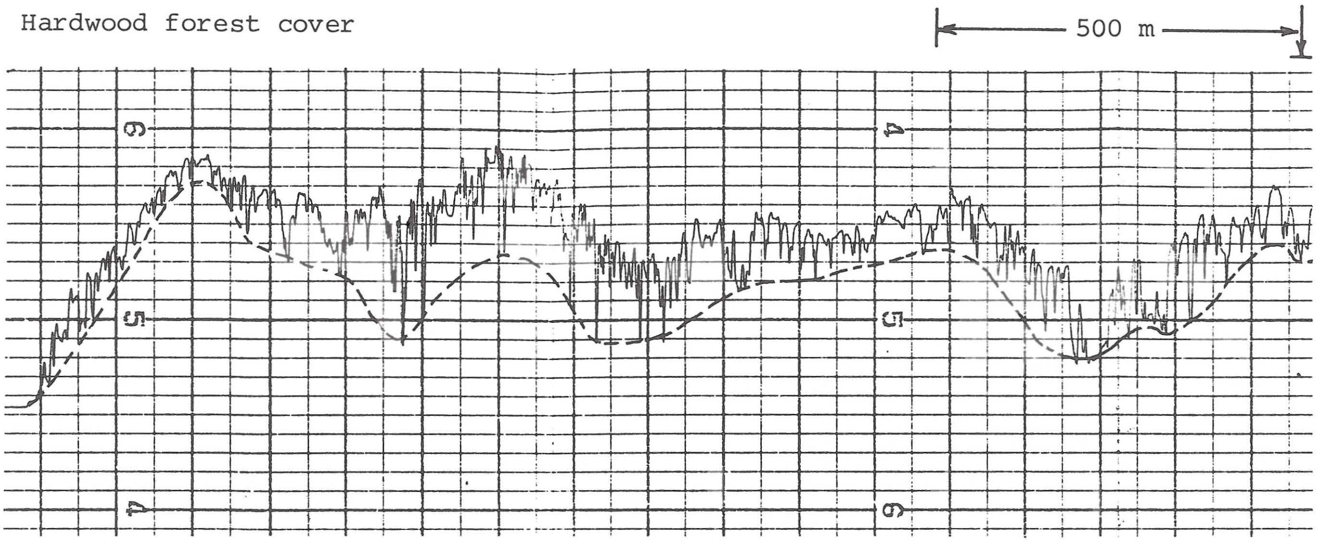
In order to carry out the analyses, the laser data had to be correlated with terrain features on the aerial photographs and, using the photo detail, with corresponding features on the ground. The original CCRS intent was to use navigation data collected during the flights, and procedures similar to those described by Gibson et al. (1981), to complete the track recovery of flight paths. However, a cutback in the budget for this project led to the use of a cheaper alternative which would circumvent the programming and computer time required to process data from the inertial navigation system. The alternative, based on the video and photographic cameras, proceeded as follows: The boresighting procedure indicated where on the monitor the laser "footprint" occurred; an arrow was affixed to the monitor to point to this footprint, because it would not otherwise be visible during daylight runs; the video coverage of the test runs was played back and correlated with coincident photo coverage using common image details. The progression of the laser footprint, by reference to the pointer, was thereby plotted on the photos. Since laser pulses are time-coded and since time is recorded and displayed on the TV monitor, each pulse could also be marked on the photos. The slow-motion, freeze-frame feature of the video playback was a great help in this respect. The flight path and numbered events on the photos thus completed the track recovery needed to correlate the laser events with the terrain features. Figure 9 shows a typical laser path along a transect.

The track recovery of the flying height laser flights followed a similar procedure, except that a tracking camera was used in place of a video system.

Softwood forest cover



Hardwood forest cover



Corresponding photo exposures

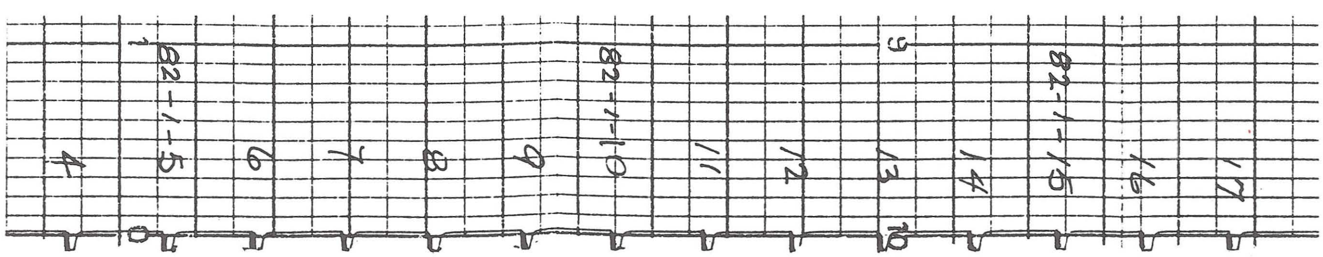


Figure 8. Altitude profiles from the production laser flown over softwood and hardwood forest cover. The corresponding photo events are shown on page 18. The dashed line signifies the probable terrain profile.

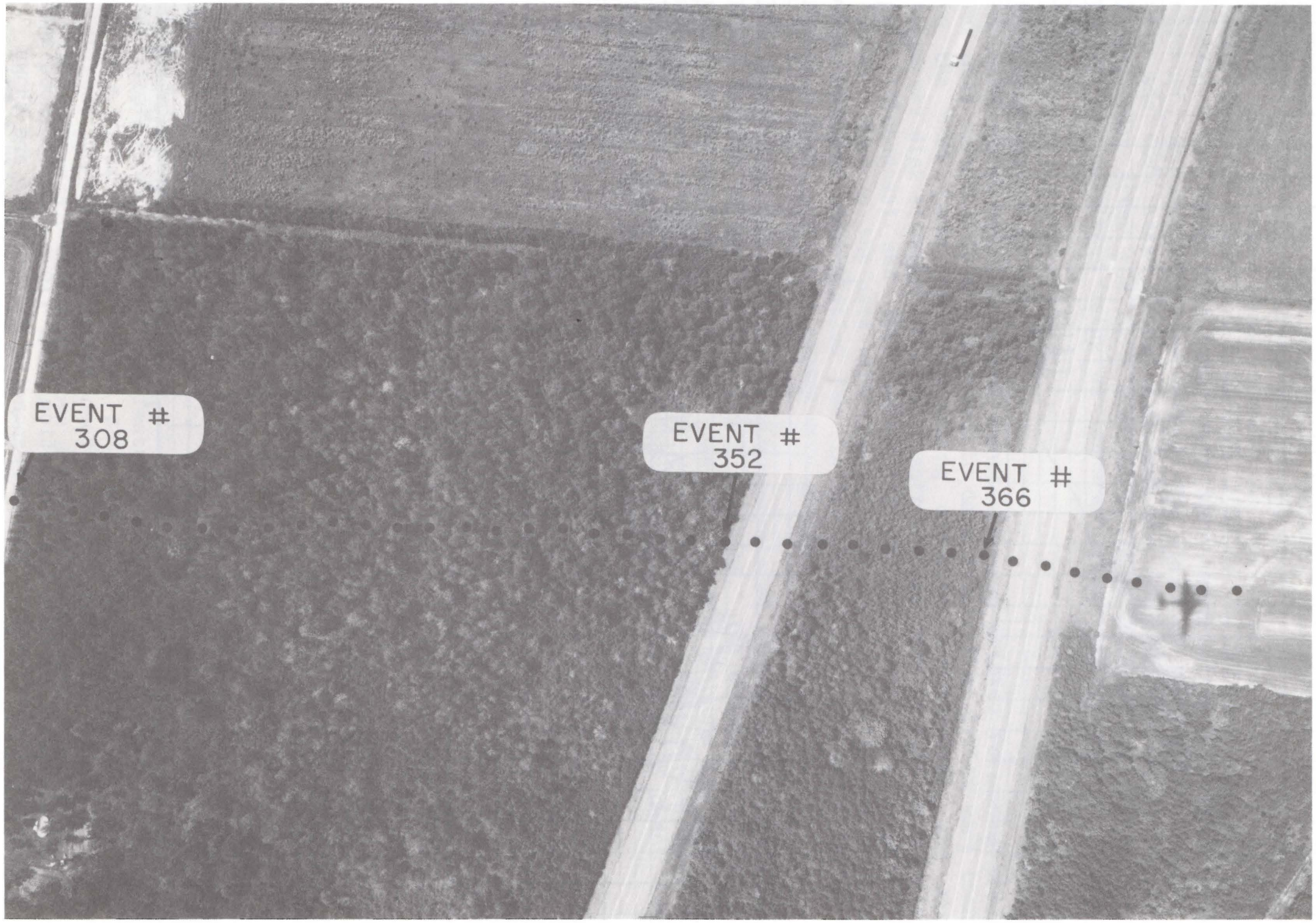


Figure 9. Portion of mapping photography showing laser track and laser samples along it. Every second sample is shown. A dot is about equivalent to the area illuminated by a 10 mR laser shot.

The instant of exposure of the tracking camera was recorded and correlated with other data such as pitch and roll attitude and flying height from the laser.

The investigation of pulsed laser data proceeded after we ascertained, in both cases, the connection between laser data and terrain features.

Analysis and results

The several tests of older, continuous wave lasers indicated that distance can be measured to within ±30 cm or better (Forest Mgmt. Inst. 1978), a level of accuracy exceeding the forestry requirement. The latest pulsed lasers theoretically are able to measure distance to an accuracy better than ±30 cm (Krabill et al. 1984). We checked the capability of the two lasers used in this project to confirm these claims.

To test the distance measurement capability of the lasers, objects visible on aerial photographs were selected, and horizontal distances between them measured in the field. Using these photo-measured distances between the pairs of points and calibrated lens focal length, aircraft-to-target distances were determined and compared with distances derived from the lasers. The differences were so small that the errors (less than 1 m) could have stemmed from the photo procedures as much as the laser range finders. Because errors less than 1 m were considered to be of little consequence to the forestry application, no further effort to improve the calibration appeared necessary. The ability of the lasers to satisfactorily measure distance from an aircraft to a well-defined target was thus confirmed.

The stand height measurement capability of the CCRS system on the Woodroffe test area (flat terrain) was tested using altitude profiles such as shown in Figure 10. The profile in the figure is inverted because the distances to nearer objects, such as the forest canopy relative to the terrain, are smaller and therefore lower along the ordinate. The stand heights were measured directly from profiles after the location of the terrain was approximated. This could be done fairly reliably in cases where breaks occurred frequently in the canopy, allowing the profile to return to ground level, or in cases where the terrain profile was flat and unbroken. To test the heights extracted from the profiles, a visit in the field was made to specific points along the profile. At these points, stand height measurements were taken. Where gaps in field samples occurred because of difficulties in locating the transect in the field or other problems, a photogrammetric profile was produced using the Canadian Forestry Service Stereocord/desktop computer/graphical plotter system. Figure 11 illustrates such a profile. The photogrammetric profile was used to fill in gaps and provide supplementary test data. These profiles should be accurate to within 1 to 2 meters on softwood and hardwood canopies, provided the hardwoods have leaves. Otherwise, the hardwood profiles are difficult to produce accurately because the image detail is poorly defined and many of the smaller branches are not resolved. The vagaries of the vertical position of the terrain continue to apply, especially under the dense conifer stands and on areas with significant relief.

To analyze the accuracy of the laser profile, heights were compared with those derived from stand measurements in the field. The mean and standard deviations of the paired differences were used to express the systematic and

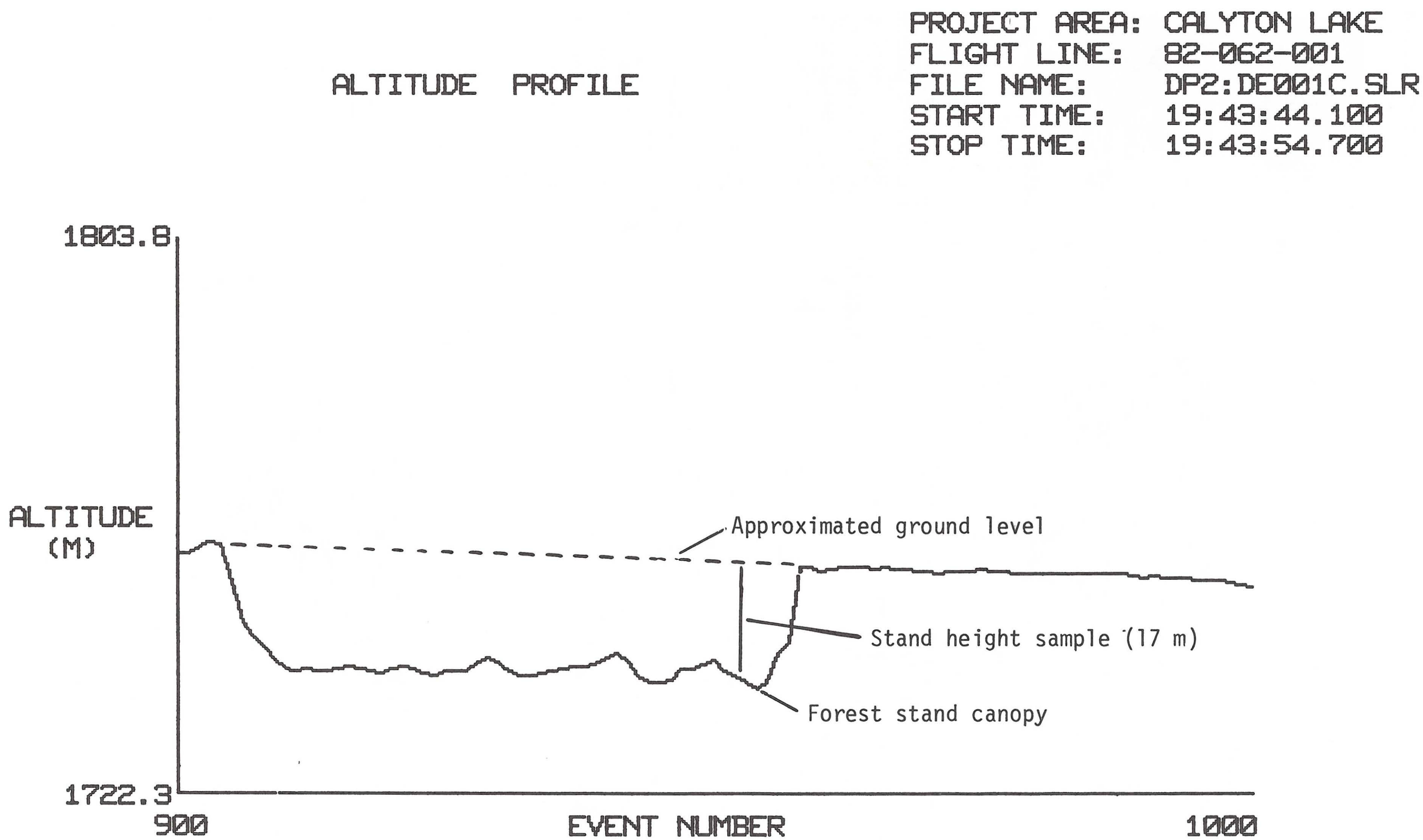


Figure 10. Altitude profile produced from slant range (distance) measurements on the CCRS lidar bathymeter system. Vertical profile of the forest stand and terrain appear upside-down.

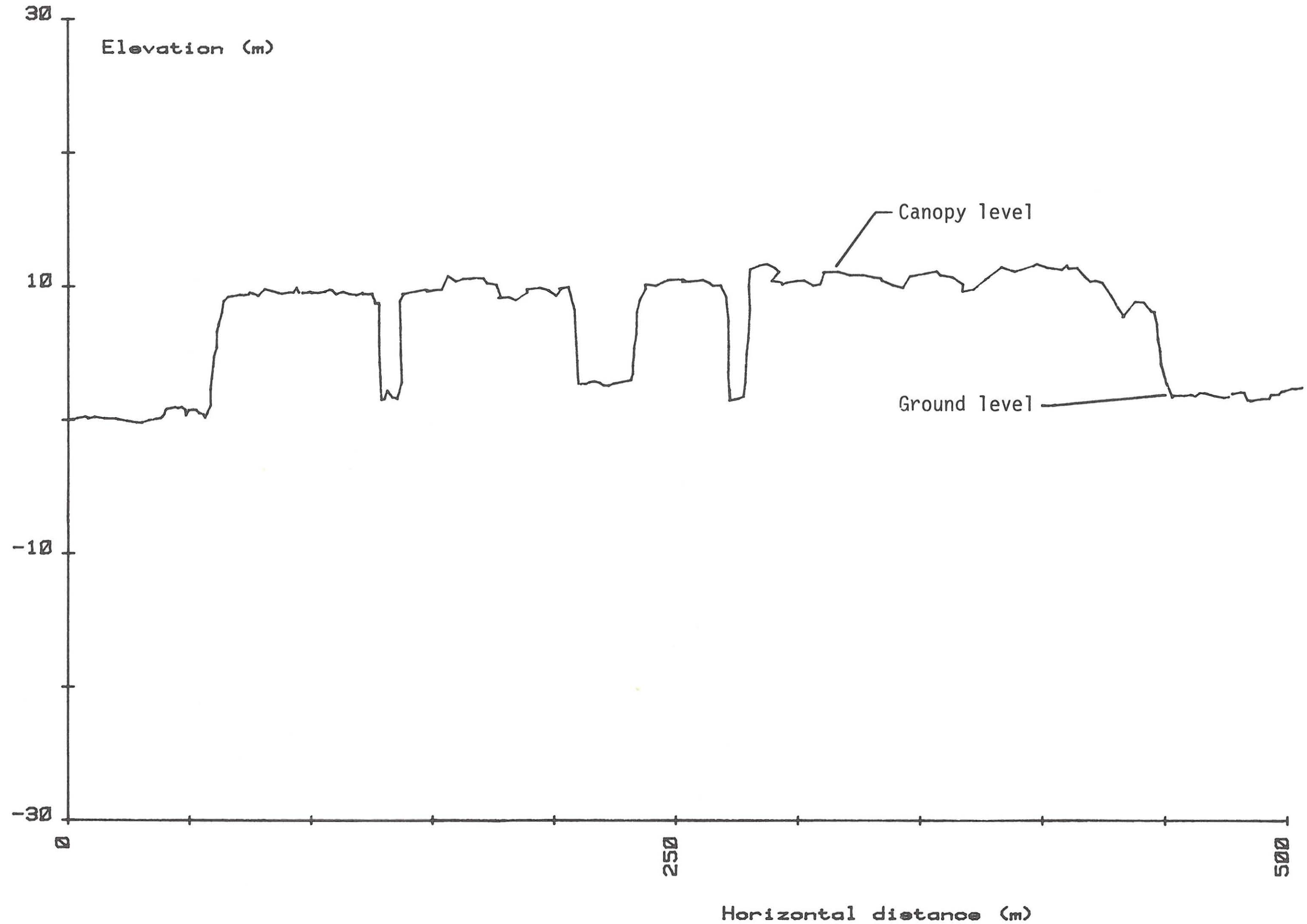


Figure 11. Vertical profile of part of the transect shown in Figure 10 produced photogrammetrically.

random components of the error, respectively. The results, shown in Table 1, indicate that a negative systematic error occurred in most cases, meaning that the laser energy was reflected not from the tops, but lower down on the larger crown surfaces as illustrated in Figure 12. An exception was the softwood/25 mR combination, which had a rather weak sample. The hardwood stands showed a larger systematic error than the softwood, as was expected because the leafless crowns afforded a less definite reflective surface. The variation, as expressed by the standard deviation of the differences (SD), followed a similar pattern. The best result (a systematic error of -0.7 m and a random error of ±1.0 m at 1 standard deviation) was obtained for softwood stands with the 5 mR beam divergence.

Table 2 shows corresponding results from the production system tested on Area 4. This laser, which uses a 2 mR beam divergence, did not respond to leafless hardwoods at all, a property which is desirable for its designed function as an aircraft-to-ground distance measuring device. The systematic error of softwood stands was about -2.6 m and the SD variation about 1.0 m. The fairly large systematic error is related to the way conical crowns of the softwoods were sampled. The sampling rate of 320 measurements per second of the production laser improved the chance of penetrating to the ground level. However, as illustrated in Figure 8, stretches of 100 m or more may occur without a definite ground return through a softwood canopy, and the leafed hardwood canopy profile in the figure shows much longer stretches of uncertainty.

The CCRS system afforded an opportunity to examine the prospect of deriving stand height data from individual pulse returns. The approach taken was to examine the plotted output of energy returns from different targets. Figure 13 shows a typical return from open ground. The X axis shows the duration in nanoseconds of a pulse return; the Y axis shows the amplitude or strength of the returned laser pulse. The waveform in this figure is about as simple and as short in duration as can be expected. This is because the returned energy is reflected back at one time. The pulse return in Figure 14, however, is a return from a building. Note that this return contains two peaks, the first (earliest) pertaining to the roof of the building and the second to the energy reflected from the ground near the building. A single and an equivalent double return pulse were illustrated in Figure 4. By measuring the time delay from peak to peak, or at some defined point on the two leading edges or trailing edges of the returned waveform, height on elevation differences can be derived. In fact, the vertical height above the ground of the roof in Figure 14 was found to be within 50 cm of that measured on the ground and checked photogrammetrically. A typical return from a leafless hardwood canopy is illustrated in Figure 15 and a typical softwood return in Figure 16. Note the distinct double echo and the relative strengths of the first and last pulses. The leading edge time differences according to different thresholds (i.e., 20% of the way up to maximum, 50%, etc.) between the peaks and between trailing edges were tested. The leading edges were found to provide the best result although only marginally better than the peaks. The 20% and 50% (also called half max) results are shown in Table 3. The 20% and 50% thresholds resulted in about the same accuracy throughout, with a slightly reduced SD (random error component) evident using the half max. The 25 mR beam divergence gave the best result for the hardwood stands and 5 mR the best result for the softwood stands. In the latter case, the

Table 1. Accuracy of stand canopy height measurements (m) as derived from CCRS laser distance measurements

	Hardwood			Softwood		
Beam divergence (mR)	5	10	25	5	10	25
Mean	-8.4	-5.1	-*	-0.7	-1.2	-2.5**
SDD	6.0	3.7	-*	1.0	1.0	3.9

* Laser failed to respond to canopy
**Small sample

Table 2. Accuracy of stand canopy height measurements (m) as derived from the production laser

	Hardwood	Softwood
Beam divergence (mR)	2	2
Mean	no response	-2.6
SDD		1.2

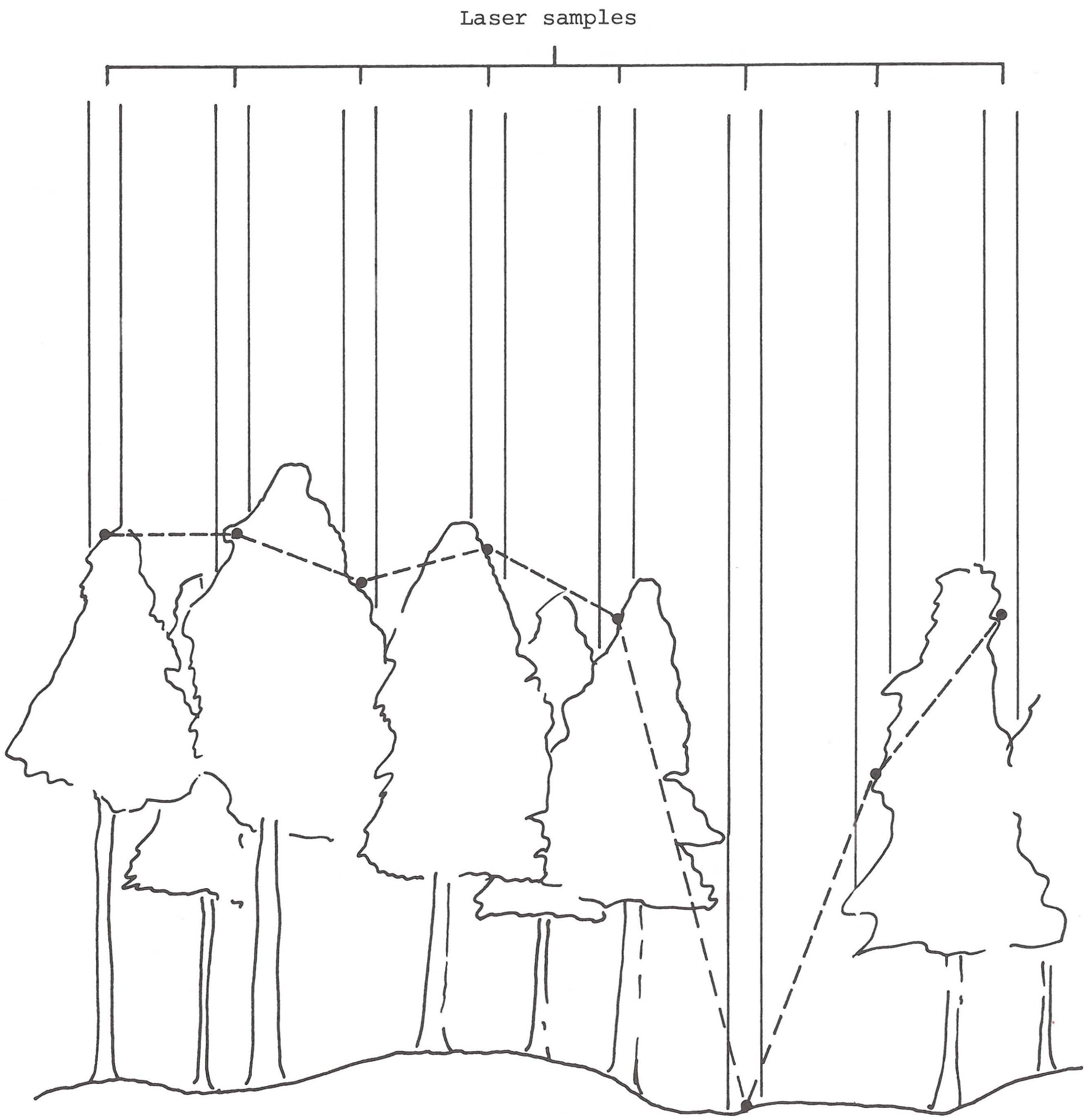


Figure 12. Diagram showing probable level in the crown canopy at which distance measurements are made. In the development of a canopy profile from the measurements (dashed line), the general canopy height is likely to be underestimated.

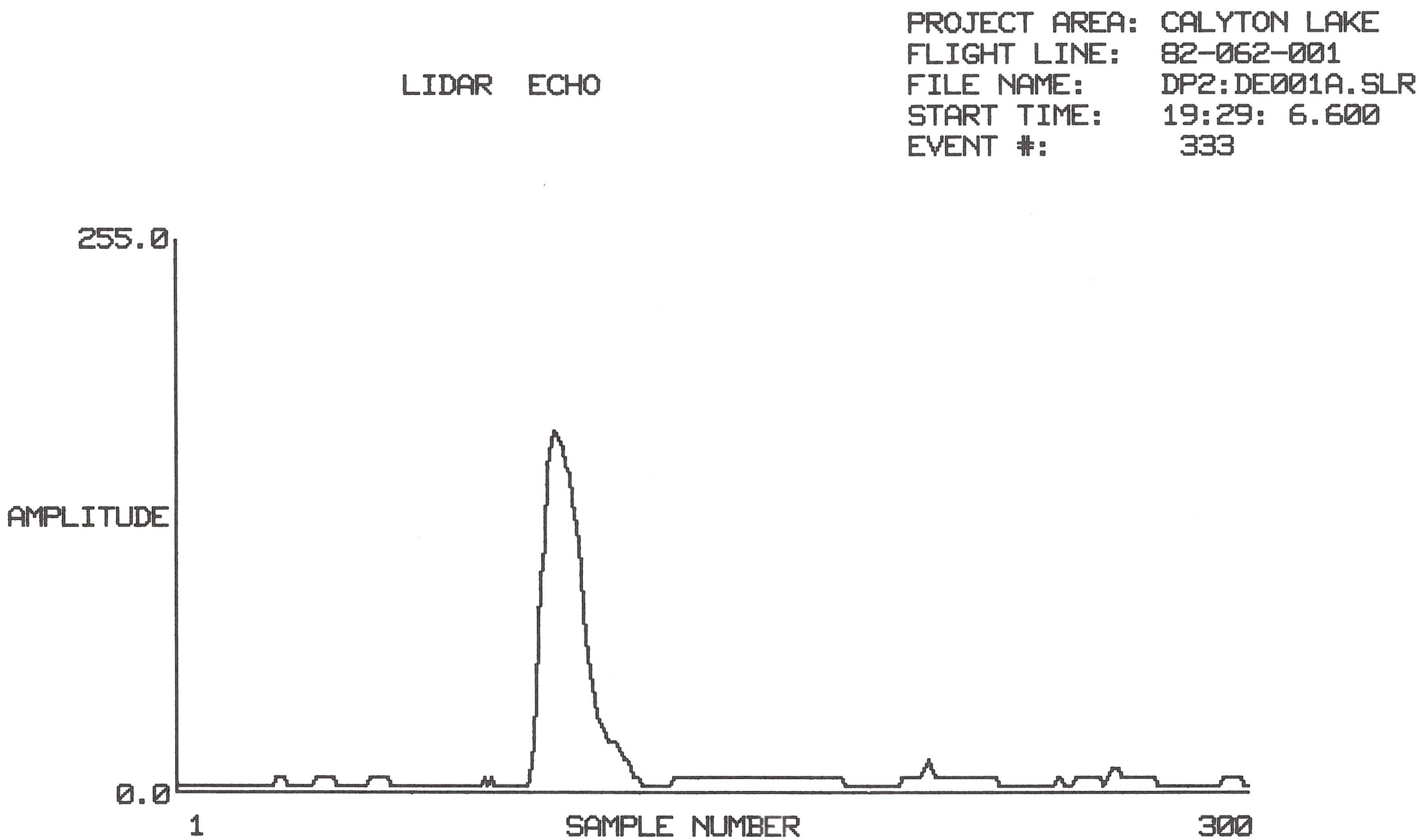


Figure 13. A typical laser echo signature reflected from open ground.

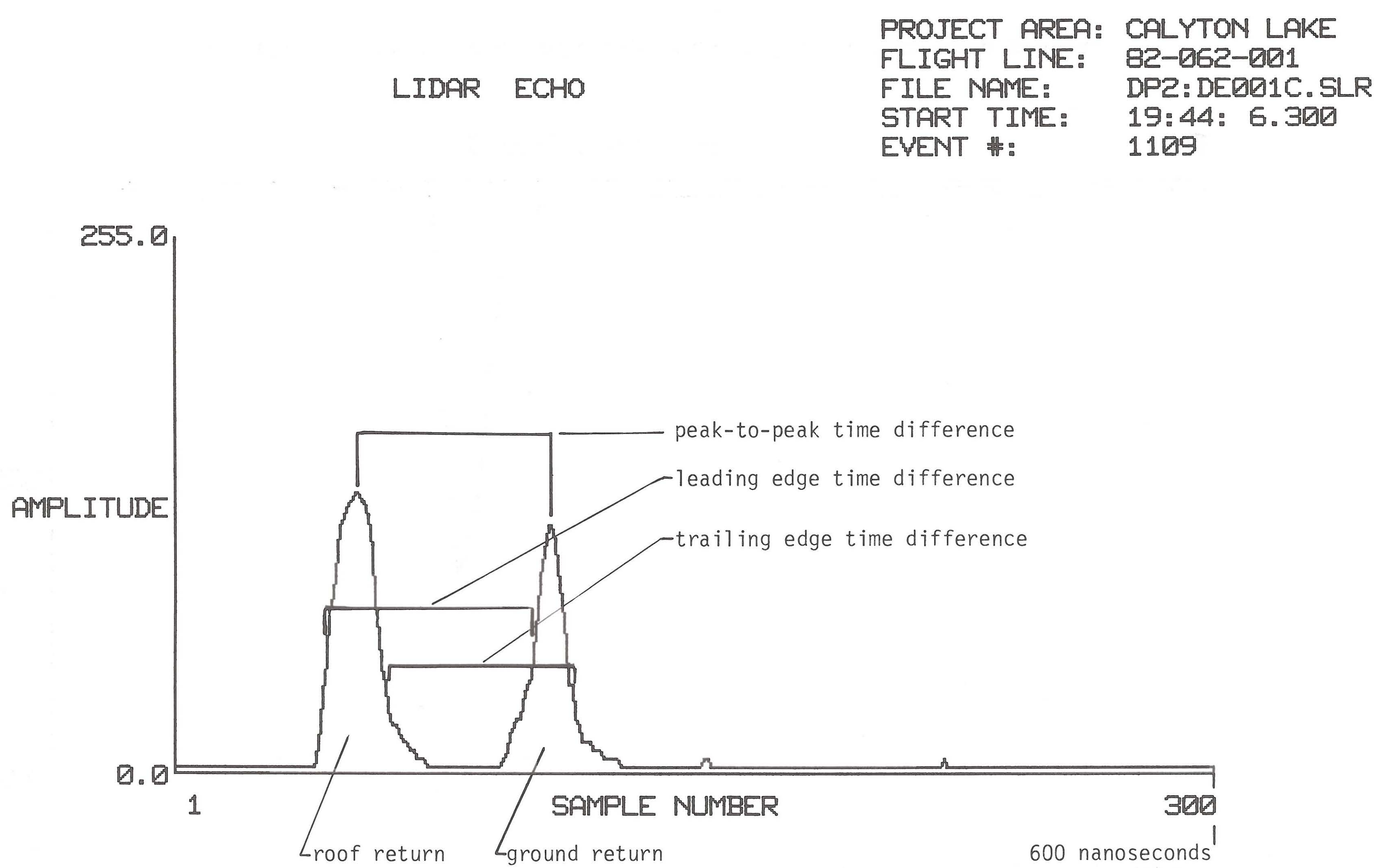


Figure 14. A laser return from a building roof and ground near the structure. The derivation of time differences and elevation differences from double echoes is shown. The peak-to-peak difference in time translates to a height of about 16 m.

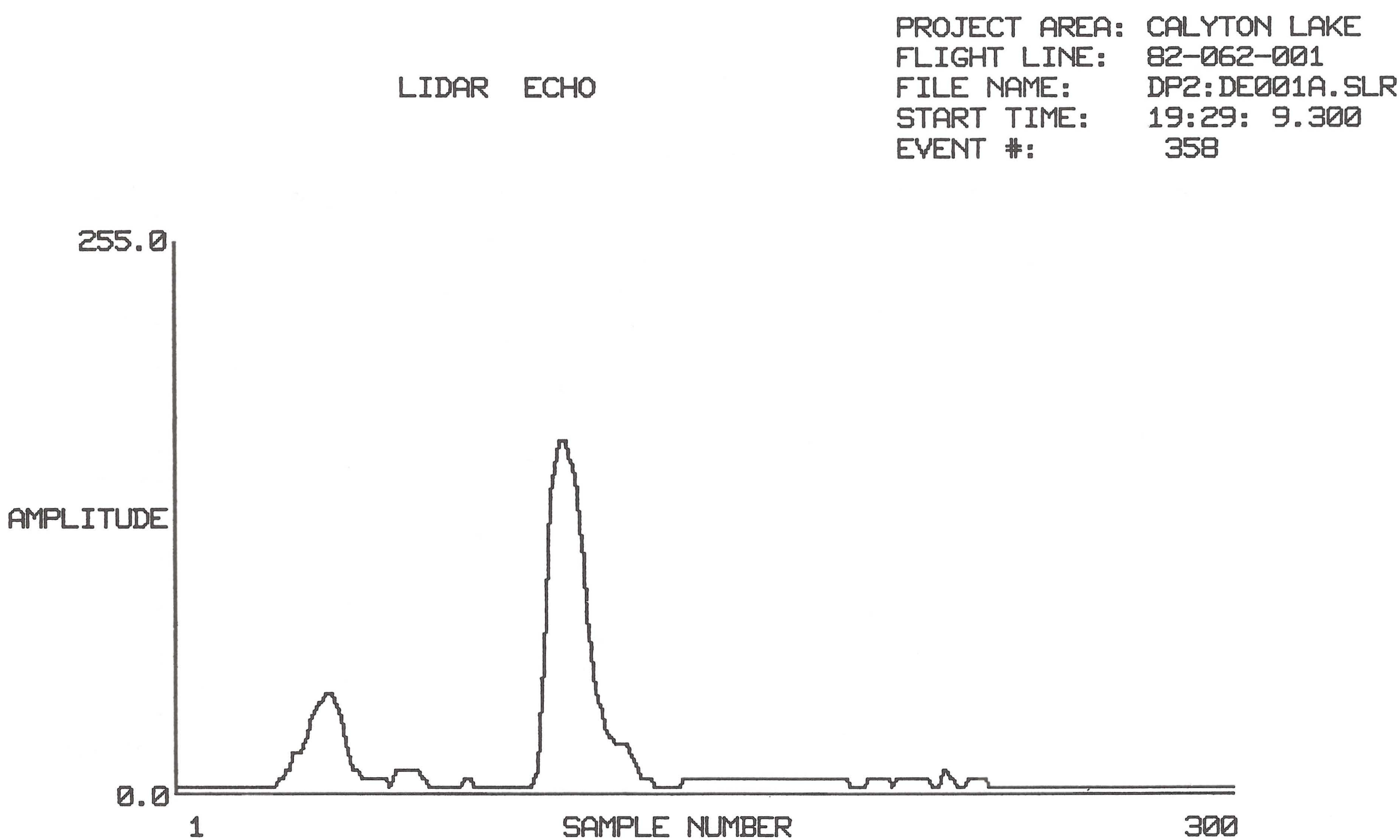


Figure 15. A typical return from a leafless hardwood stand. Note the weak return from the canopy level and the relatively strong return from the ground. The peak-to-peak difference translates to a height of about 20 metres.

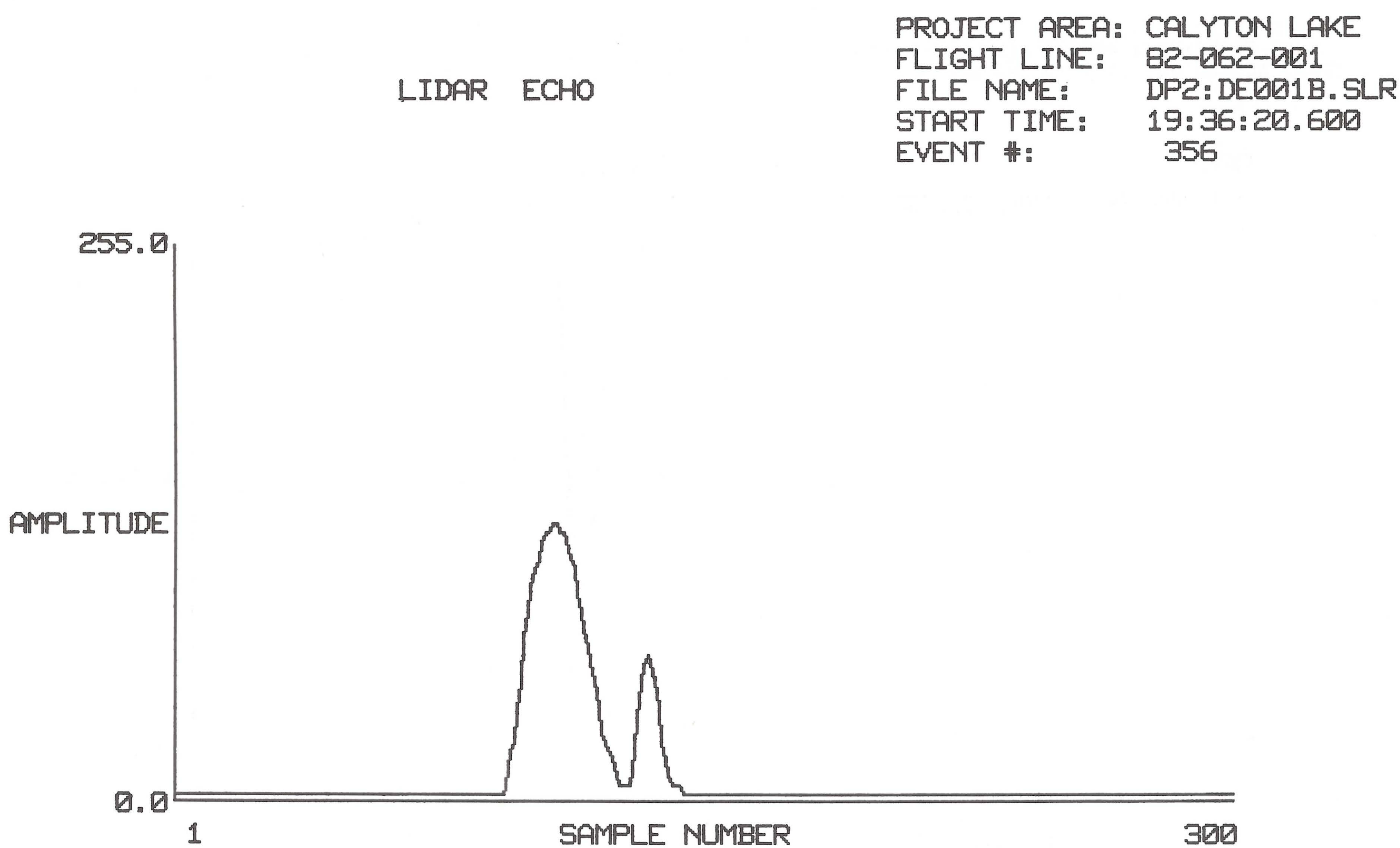


Figure 16. A typical laser return from a softwood stand. Note the strong first pulse and weaker ground return.

Table 3. Accuracy of canopy height as derived from individual pulses

	Hardwood			Softwood		
Beam divergence (mR)	5	10	25	5	10	25
20% Threshold						
Mean*	-6.6	-5.0	-1.8	-0.2	-0.9	4.4
SDD**	4.8	3.1	2.8	1.2	1.3	4.9
50% Threshold						
Mean	-5.8	-5.2	-0.5	-0.8	-1.2	5.6
SDD	4.9	2.9	2.6	1.0	1.0	4.9

*Mean of differences between laser and ground-decimal forest canopy heights (systematic effect).
**Standard deviation of differences (random effect).

25 mR setting produced an unexplained positive systematic error and a high SD.

Phase 1 conclusions
The use of slant range (distance) data from laser profilometers is unlikely to provide reliable stand height information, especially where significant topographic relief and dense forest canopies occur together. However, the rapidly pulsed (320 measurements/s) production laser was found to penetrate the canopy more frequently than the 10 measurements/s CCRS laser. The production laser ignores the canopies of leafless hardwoods, providing a reliable profile of the terrain but no forest information. The leafed hardwood canopies were the most difficult to penetrate by the production system. In general, vertical profiles generated from distance data are of limited value in obtaining forest canopy information, and should not be pursued further except possibly for terrain profiling applications.

The treatment of individual pulse return waveforms appeared to offer a promising means of sampling canopy height (i.e., penetrating the forest canopy) and, in conjunction with slant range, of finding aircraft-to-terrain distance, regardless of the presence of forest cover. From the limited testing carried out, the individual pulses enable stand height to be measured to within about ±3.0 m and ±1.0 m (66 per cent level) for hardwood and softwood stands respectively. The higher variation for the hardwoods is explained by their leafless condition, the twigs and branches providing a less well-defined reflective surface. The laser beam divergence and species composition appeared to interact in their influence on height measurement variability. This requires further testing to pin down. The systematic effects were generally negative, relating partly to the inability of the system to detect weak returns from the extreme tops of softwoods and fine twigs of the leafless hardwoods, and partly to where in the canopy the samples fall. The results vary with beamwidth, species composition and height discrimination. Species composition, crown cover density, hardwood leafing, and sloping or broken terrain were identified as important areas of investigation in the next phases.

It was also considered desirable to modify the production laser so that individual pulse return waveforms could be captured. This was to allow certain interesting properties of the low-powered laser to be investigated.

Phase 2

DEVELOPMENT OF PROCEDURES TO EXTRACT FOREST STAND INFORMATION

During the preliminary investigations in Phase 1, the waveforms from individual laser pulses were found to provide promising data on stand height and density. A high proportion of the pulses were found to penetrate the leafless hardwood and coniferous stand canopies. Many questions, however, were left unanswered and procedures had not been developed to produce forest stand estimates of height and density for runs of many pulses.

Objectives

To address some of the questions and to start the development and testing of procedures, the following were pursued in Phase 2:

1. The Phase 1 results were confirmed by a second, independent series of tests using the three selected test areas in Phase 1. The second test series was designed to resolve anomalies appearing in the first series.
2. The processing of individual pulses were developed and tested further under a wider range of forest stand and terrain conditions.
3. Similarly, some hardware characteristics such as beam divergence were tested further.
4. The production laser was modified so that individual pulse returns could be captured and analyzed.
5. The leafed hardwood condition was tested.
6. Data reduction procedures were developed and tested to handle the production of forest stand information from runs of many pulses over forest stands. This step prepared for the formal testing to be conducted in Phase 3, focusing on evaluating the effectiveness of pulsed lasers in providing stand information.

Procedure

A second series of flights over test areas 1 to 3 was completed by CCRS on July 13, 1983. The aforementioned CCRS equipment configuration was used, except that the production laser was added to the system. Identical flight specifications were followed with the exception of flying height. Flying height was dropped from 850 m above ground level to 400 m because the production laser does not work reliably over 500 m.

The test and analysis procedure was still informal, following the same approach described in the Phase 1. The emphasis, however, shifted almost entirely to the analysis of multiple returns from individual pulses, and treating the effect of specific variables such as beam divergence, stands of varying species composition, seasonal effects (hardwood leaves on), data reduction method, and combinations of these factors. The factors were treated together so that possible interactions could be identified. During the treatment of these effects, methodology was developed for processing runs of many pulse returns and the production of forest stand information. Stand height was investigated first and density and species composition brought in later.

The more formal statistical procedure for testing and evaluating the effectiveness of pulsed lasers as a means of producing forest stand information was developed. This included the postulation of some hypotheses concerning the type and reliability of information that could be produced. The formal testing itself was treated in Phase 3 where the procedure is described.

Analysis and results

The production laser was modified, interfaced to the CCRS data acquisition system, and included in the second test flight. The production laser, however, failed to produce usable pulse waveforms for analysis. The failure was caused by the modification tapping into the instrument's internal discriminator instead of the power output from the receiver.

The effect of beam divergence, species composition, and the presence or absence of hardwood leaves on the accuracy of the stand height measurements was treated together in a common framework. This was done by identifying flight transects covering each of these conditions and then selecting examples for testing. Random selection was not followed at this informal testing stage because it was desirable to treat some extreme cases first.

From the analysis of individual pulses, the results in Phase 2 generally confirm those obtained in Phase 1. The systematic errors of stand height determination, as expressed by the mean of differences between the laser derived height and the field counterpart, are shown in Table 4. The softwood systematic error remained at about -1.5 m, reflecting the tendency for detectable pulse returns from the crown to be somewhat below the conical tops. This effect was noted in Phase 1 and was anticipated because of the diminished reflective surface near the tops. A similar effect was found in tests of hardwood stands; however, the error was found to be strongly related to beam width, that is, the wider the beam, the less the error. This tendency was less evident in softwoods. The unexplained large positive systematic error in softwood stands associated with the 25 mR beam width in Phase 1 did not

Table 4. Systematic errors in the measurement of stand height from individual laser pulses expressed by mean of differences between laser and field height (m)

	Hardwood						Softwood		
	Leaves on			Leaves off					
Beam divergence (mR)	5	10	20	5	10	20	5	10	20
Discrimination Method									
20% Threshold	-6.0	-2.4	-1.4	-6.6	-5.9	-1.8	-1.5	-1.6	-1.3
50% Threshold	-6.8	-3.5	-1.7	-5.8	-5.2	-0.5	-1.9	-2.0	-1.7
Peak-to-peak	-7.2	-4.2	-2.9	-9.1	-7.7	-2.7	-2.8	-3.2	-3.2

reappear in Phase 2. The systematic errors associated with foliated hardwoods differed from the unfoliated counterpart mainly in the 10 mR case, the error being less (-2.4 m) for the leaf-on case. Otherwise, the trend of reduced systematic error with increased beam divergence was nearly identical for the leaf-on and leaf-off conditions.

The random error component, as expressed by the standard deviation of paired differences, was small for softwoods and considerably larger for hardwoods (Table 5). The difference most probably relates to greater uniformity in crown canopy height and density of the softwood stands tested (plantations), and the greater ease and accuracy of height measurement in the field. The larger random error apparent in the hardwoods may also stem from difficulties in locating the laser shots exactly and then sampling the area covered by the shots in a representative way. In the first series the random errors did not seem to be strongly related to beam divergence. In the later series, both hardwood and softwood standard deviation of differences declined slightly as the beam width increased. This pattern probably relates to the "averaging" effect of reflections from a larger target area.

The random errors associated with foliated hardwoods were somewhat larger than the unfoliated condition (Table 5). The trend of reduced random errors with increased beam divergence remained.

During the preliminary analysis of individual pulses, several discriminators for obtaining height information from waveform data were tested. The peak-to-peak and leading edge discriminators were found to yield better results than trailing edge discriminators. During this part of the project, a much wider range of leading edge thresholds were tested--1 per cent up to 100 per cent of the maximum height of the first peak--in order to select the optimum threshold. The different thresholds were tested on 17 multiple returns over stands of known height. Both hardwood and softwood stands were included. A linear regression relationship was established between control height and the height generated from laser returns. Regression analysis allowed scalar as well as systematic effects to be examined and the performance to be assessed in terms of residual error. The optimum was judged in terms of minimum residual error. As can be seen from Table 6, residual error was relatively insensitive to the selected threshold. The optimum was around the 85 per cent level but the peak-to-peak discriminator (at a threshold equivalent of 100 per cent) was nearly as good. The 85 per cent threshold regression relationship is shown in Figure 17. As noted earlier, the laser heights were consistently about 2 m lower than the standard. A minor scalar effect was evident.

In order to improve the means of representing the area covered by a laser shot, other methods of ground sampling were tried. One approach was to take a cluster of height samples over the laser and use the average of these height measurements as the test standard. The results of this approach are shown in Table 7 for the 5 mR beam width. The systematic error was reduced slightly but the random component was somewhat larger. Not much was gained from this approach.

Several other efforts were made to improve the accuracy of discriminators. These included using several criteria for rejecting height readings which did not contain multiple returns or which lay outside the range

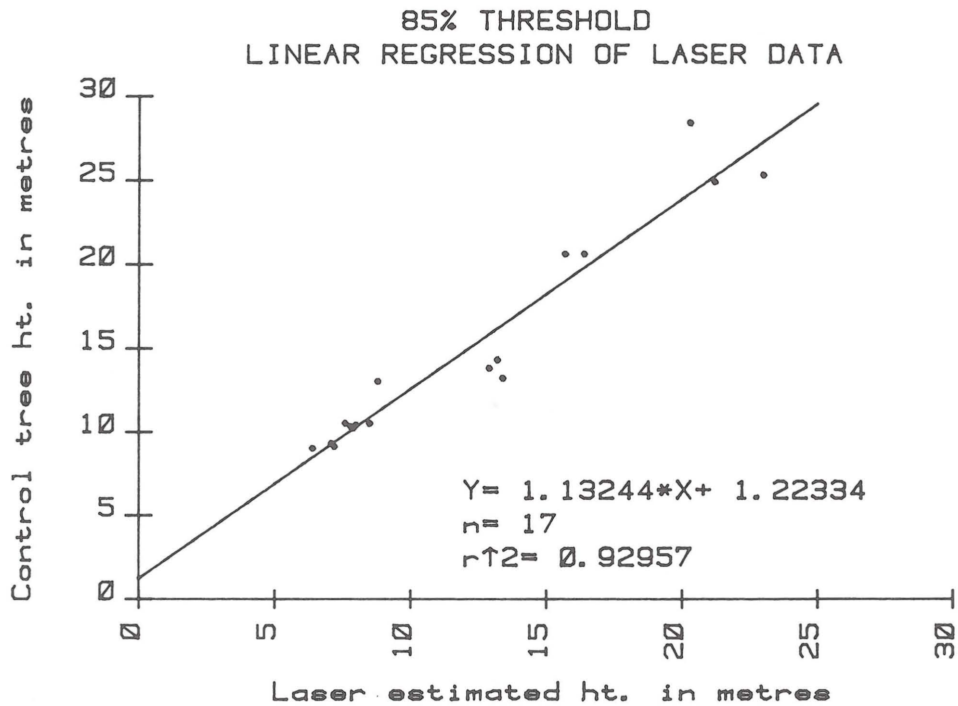
Table 5. Random errors in the measurement of stand height from individual laser pulses expressed by standard deviation of differences (m)

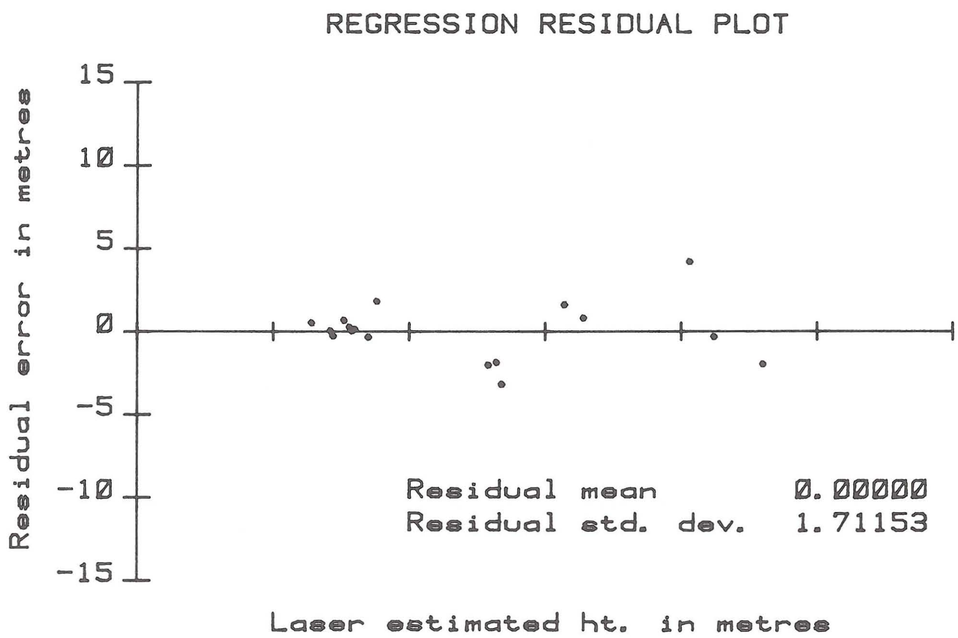
	Hardwood						Softwood		
	Leaves on			Leaves off					
Beam divergence (mR)	5	10	20	5	10	20	5	10	20
Discrimination Method									
20% Threshold	6.6	5.5	5.1	4.8	3.1	2.8	1.9	1.8	0.7
50% Threshold	6.3	5.7	4.6	4.9	2.9	2.6	1.8	1.6	0.9
Peak-to-peak	6.2	5.5	4.5	7.0	4.4	4.0	1.5	1.4	0.9

Table 6. Threshold determination

No. of Samples = 17

Threshold %	R^2	Residual standard deviation
100	0.928	1.721
95	0.929	1.716
90	0.928	1.732
85	*0.930	*1.712
80	0.928	1.728
75	0.926	1.757
70	0.926	1.759
65	0.926	1.753
60	0.924	1.774
55	0.923	1.792
50	0.921	1.807
45	0.920	1.821
40	0.919	1.836
35	0.920	1.827
30	0.919	1.837
25	0.916	1.866
20	0.911	1.920
15	0.909	1.944
10	0.900	2.044
5	0.900	2.042
1	0.910	1.931





DENDRON GRAPHICS

Figure 17. Regression relationship between field height and laser estimates of stand heights from multiple-return pulses.

of expected stand height. For example, if some preceding laser data or other a priori information were at hand to anticipate a stand height of say 20 m, all readings exceeding ±10 m of 20 m could be rejected and the accepted ones used to revise the central value of 20 m. Some function of the standard deviation or other expression of variability could also be used to revise the range as well. This "window" concept was tried with a significant reduction in both the systematic and random components of error (Table 8). However, the choice of a suitable window was considered arbitrary and would have to vary with the particular forest or stand condition. It was felt that this would detract from a general assessment of the laser technology. Accordingly this line of investigation was discontinued. For particular situations, though, use of a carefully defined window could be expected to improve the results substantially. The rejection of pulse returns with only one peak, containing no height information, was considered necessary. The classification of such pulse returns was required in any event for the later treatment of crown cover density.

Stand height

As methods of classifying pulses were developed, the emphasis accordingly shifted from analyzing the information content of individual pulses to that of runs of many pulses over relatively uniform areas of forest cover. The development work concentrated on stand height but also prepared data for simulating crown cover density and cover type. The methods were based on treating a series of pulse returns covering a particular stand which had been delineated on air photos. The returns were passed through the height measurement discriminator and classified as having multiple returns or just a single return. The single return was treated as having no stand height information. The multiple returns were further classified as having two, three, four, or more peaks. The first and last were used together with the 85% threshold discriminator to generate height values. These were subsequently averaged with others to yield a stand height estimate.

The results illustrated in Figure 18 and given in Table 9 agreed generally with results based on the analysis of individual pulse returns. However, in Table 9 the main systematic effects have been isolated and removed since they were considered to hold consistently. Those shown were residual effects which remained after the adjustment. The calculation of the root mean squared (RMS) error in Table 9 was used as a means of reflecting the joint effect of both the unaccounted-for systematic error and random measurement error. At this tage, RMS was a useful single quantity for measuring accuracy. An RMS of 2.4, for example, for all hardwood stands means that an estimate of stand height should be within ±2.4 m of the actual height two thirds of the time.

As noted earlier, stand height measurement error declined as the softwood content increased. Pure softwood stands had an RMS of about 1.6 m. However, few data were available for such stands. This limited the certainty of conclusions that could be reached on the combined effect of softwood species and beam divergence. For hardwood and mixedwood stands, the effect of beam width on accuracy was minor, although a slightly lower RMS error was evident for the 10 mR beam divergence.

Table 7. Accuracy of stand height as derived from individual pulses and compared with clusters of field data

	Hardwood		Softwood	
Beam Divergence (mR)	5		5	
Discriminator	Cluster	Non-cluster	Cluster	Non-Cluster
20% Threshold				
Mean difference	-7.2	-6.0	-1.9	-1.5
Standard deviation of differences	6.3	6.6	1.7	1.9
50% Threshold				
Mean difference	-7.9	-6.9	2.3	-1.9
Standard deviation of differences	6.0	6.3	1.6	1.8

Table 8. Difference between stand height derived from laser pulses by different procedures compared with field standard

	Average height (m)	Cut-off criteria: Middle 67%	Upper 85%	Top 20%	Top 25%	Unmodified
Softwood	10.4	-2.1	-1.2	--	1.3	-2.2
Hardwood	12.9	-3.3	-2.7	-0.0	-0.3	-4.0
Hardwood	13.1	0.6	2.0	6.1	5.7	0.3
Hardwood	9.2	-2.6	-1.5	2.2	1.7	-2.2
Hardwood	14.2	-0.0	0.6	4.0	3.6	-0.8
Hardwood	10.5	-1.9	-1.0	2.2	1.9	-2.1
Hardwood	13.8	-0.5	0.3	3.8	3.5	-0.9
Softwood	10.3	-2.0	-1.7	-0.3	-0.5	-2.2
Hardwood	28.4	-6.2	-5.8	-2.2	-2.6	-8.1
Softwood	10.2	-1.6	-1.4	-0.4	-0.5	-1.9
Hardwood	24.8	-2.0	-1.7	1.4	1.1	-3.4
Softwood	10.4	-1.5	-1.4	-0.7	-0.8	-1.6
Mean of difference =		-1.9	-1.3	1.4	1.1	-2.4
S.D. of difference =		1.7	1.9	2.5	2.3	2.1

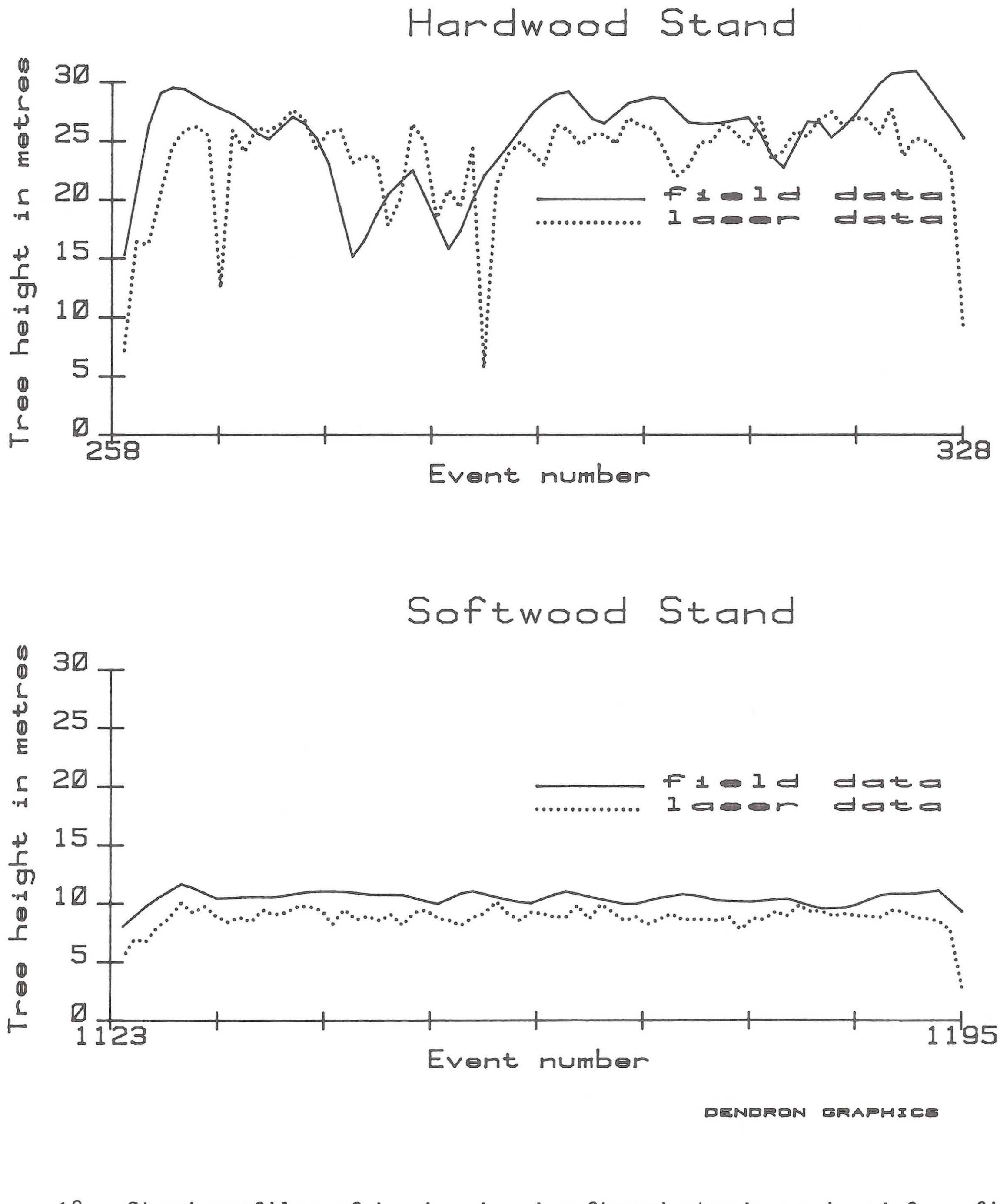


Figure 18. Stand profiles of hardwood and softwood stands produced from field measurements, compared with laser estimates.

Table 9. Accuracy of stand height measurements using runs of laser returns for fine beam divergence and three crown classes

Beam divergence	Error type	Hardwood	Mixed	Softwood	combined
1 mR	Mean[1]	0.8	-2.1	1.8	-1.3
	SD[2]	2.0	1.2	-[4]	1.9
	RMS[3]	2.1	2.4	-	2.2
2	Mean	5.1	-2.0	-1.1	-1.3
	SD	-	1.6	-	2.6
	RMS	-	2.6	-	2.9
5	Mean	-1.3	-1.2	1.5	-1.0
	SD	2.1	3.2	-	2.5
	RMS	2.5	3.4	-	2.7
10	Mean	0.9	0.2	-0.2	0.4
	SD	1.8	1.1	-	1.3
	RMS	2.2	1.1	-	1.4
20	Mean	1.3	1.3	1.0	1.3
	SD	2.2	1.1	1.1	1.4
	RMS	2.6	2.0	1.5	1.9
All divergences combined	Mean	0.4	-1.0	0.7	
	SD	2.4	2.0	1.2	
	RMS	2.4	2.2	1.6	

[1]Mean of difference between stand height measured by laser and that established as the test standard.
[2]Standard deviation of differences.
[3]Root mean squared error.
[4]Insufficient data.

Stand and terrain profiling

The stand and terrain profile was created by plotting data collected from both the laser's infrared and green beams. The infrared beam was designed with a cut-off discriminator which, as soon as the infrared beam pulse starts to return, converts elapsed time into slant range and stores it in the appropriate event record. Because no pitch and roll data were available, no correction to slant range was possible to account for changes in aircraft attitude. The slant range data was divided by two to determine the one way distance from the aircraft to the ground feature, and then plotted. In Figure 19 the converted stand range data was plotted as a solid line which followed the surface contours of objects encountered along the flight path. Additional stand profiles are shown in Figures 20 and 21.

After the green beam data were processed into tree heights, they were plotted as dotted vertical lines underneath the slant range profile. The base of each tree height was then joined to represent the ground profile beneath the tree canopy. However, if a sample was drastically higher or lower than

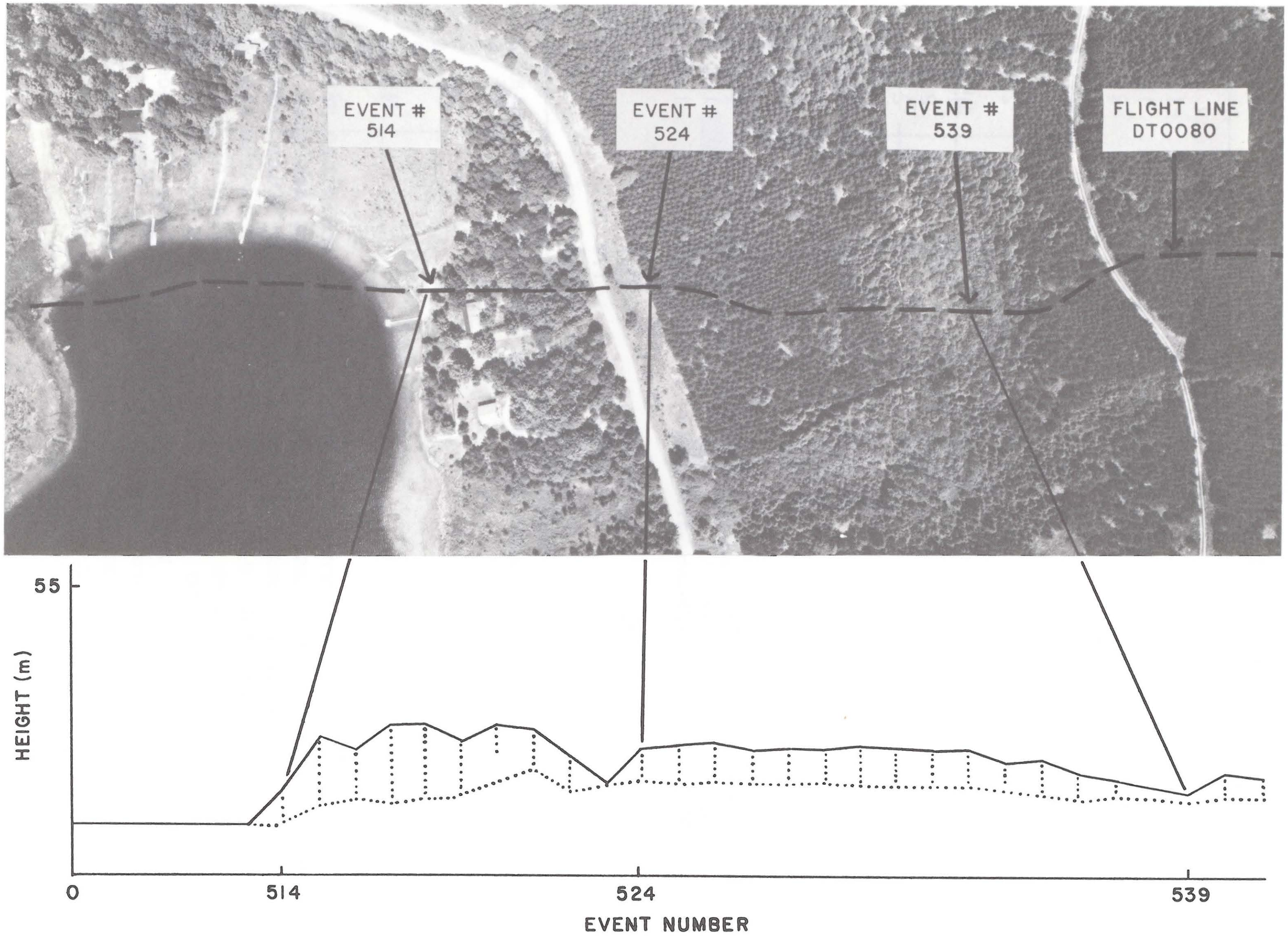


Figure 19. (Above) An illustration of the laser path plotted on a tracking photo taken during a test flight. (Below) A forest stand canopy and terrain profile produced along the flight path using laser generated aircraft-to-canopy distances, and stand height data from the processing of multiple laser returns.

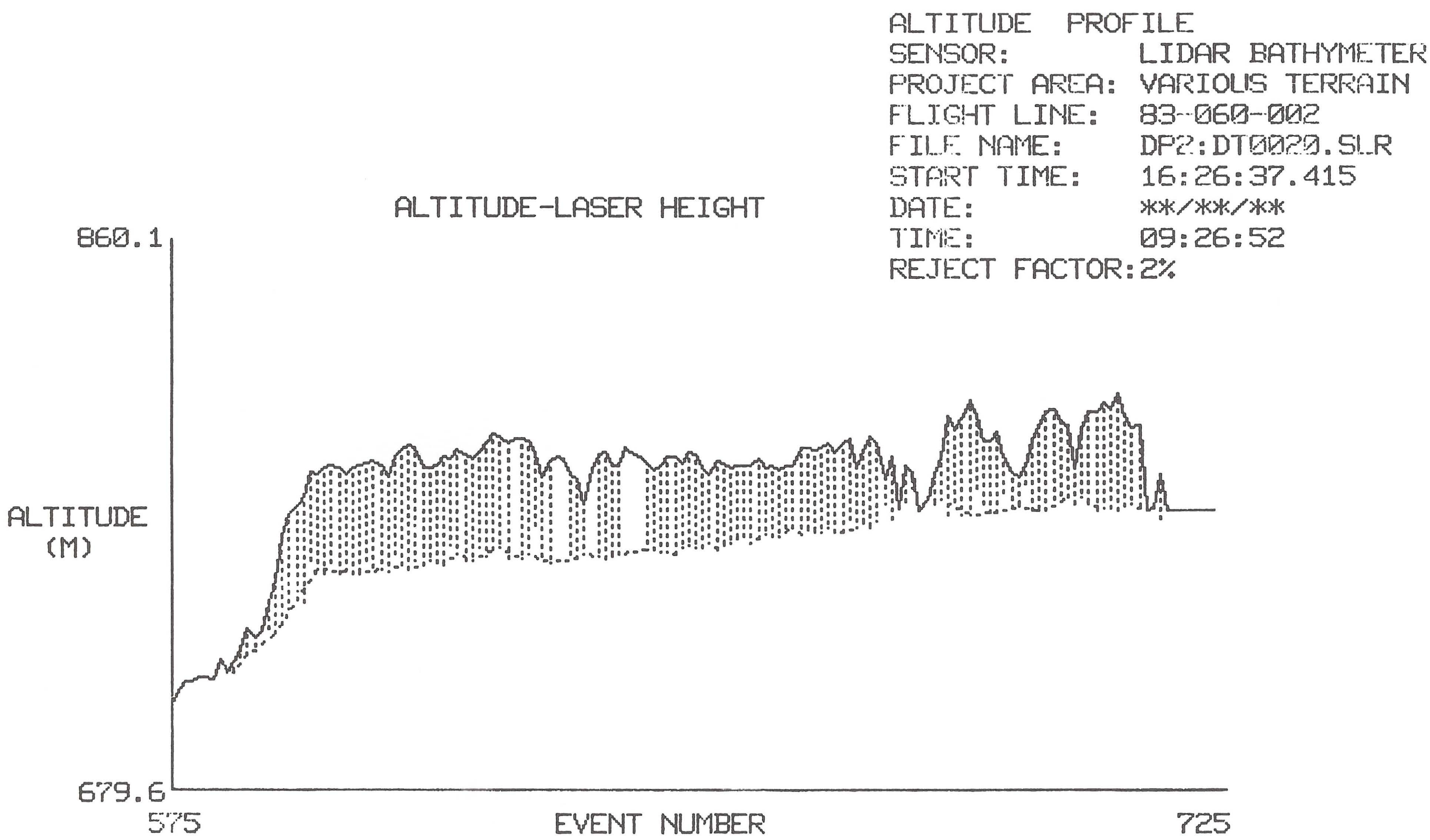


Figure 20. Terrain and hardwood stand profiles generated from first/last pulse returns combined with range (flying height) data. About 15 per cent of the pulses failed to penetrate the canopy cover to the forest floor.

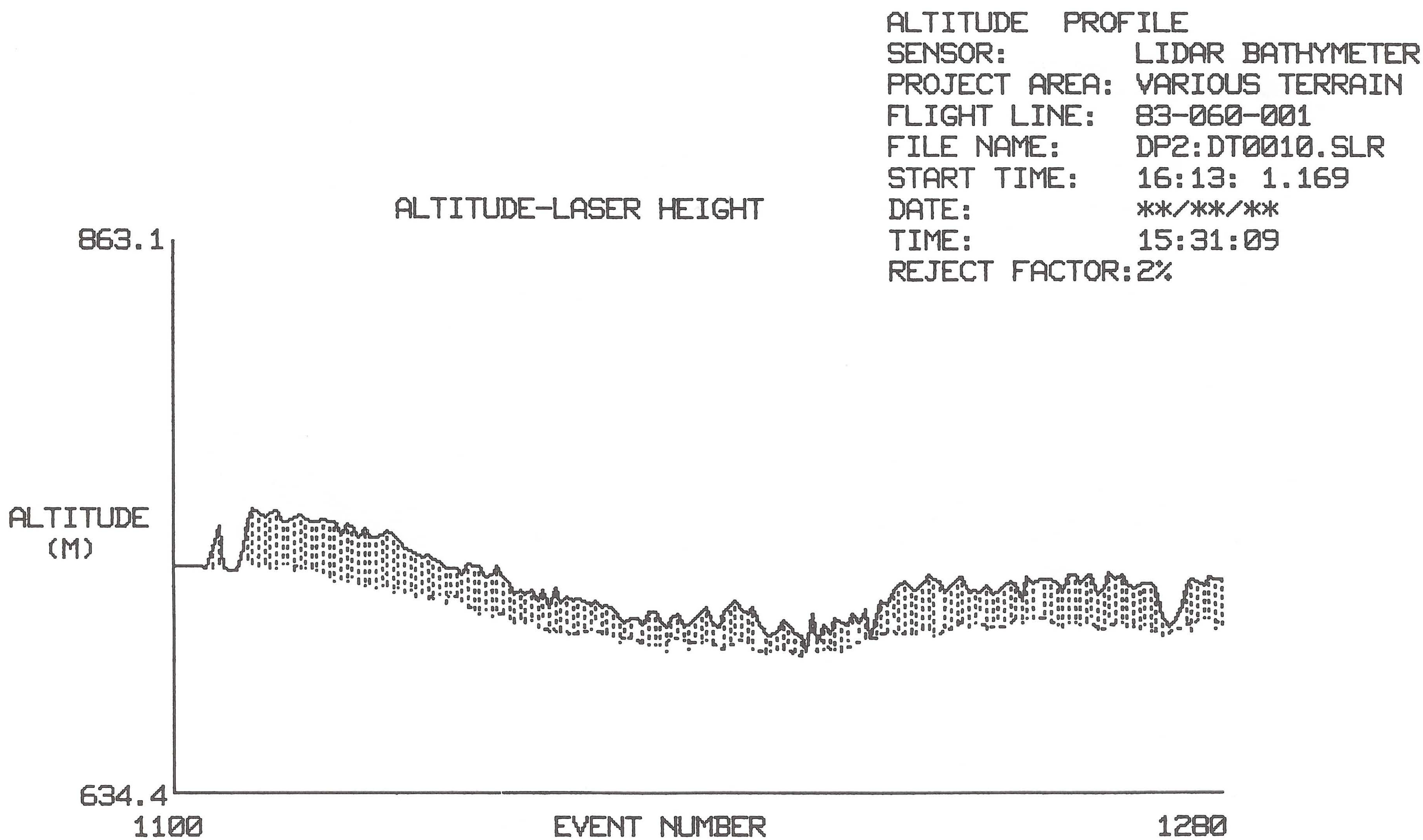


Figure 21. Terrain and softwood stand profiles generated from first/last pulse returns combined with range (flying height) data. About 5 per cent of the pulses failed to penetrate the canopy cover to the forest floor.

neighbouring points, that point was not used in plotting the ground profile. This avoided abrupt changes or distortions in ground profiles caused by pulses which failed to penetrate the canopy completely.

Crown cover density

The same approach and variables used to measure stand height were utilized in the estimation of the crown cover density of stands. The following variables were investigated:

Missing pulses:	Percentage of total number of pulse returns of a stand having only a single peak
Peak 1:	Average maximum amplitude of returns from canopy (all but last peak)
Peak 2:	Average maximum amplitude of ground return (last peak)
Amplitude ratio:	Average ground to canopy amplitude ratio
Number of peaks:	Average number of peaks per multiple return
Total area:	Average total area under the pulse return
Ground area:	Average area under the ground portion of the multiple return (i.e., under last peak)
Canopy area:	Average area under the canopy portion of a multiple return
Height:	Average height of stand

The derivation of some of these variables is illustrated in Figure 22.

As explained, the control data for crown canopy density was determined photogrammetrically by measuring accumulated length of the flight transect falling on live tree crowns and expressing it as a percentage of total length of the transect on the stand. This was found to be the best means of physically associating the measure of density with laser data.

The relationships between crown cover density and laser variables were then analyzed using correlation and regression techniques. The possible effect of laser beam divergence was also examined. The relationships were judged in terms of "goodness of fit" as expressed by the regression standard error. The best models always involved the missing pulse and average power of the ground return. It was found that the higher the proportion of single pulse returns the less dense the stand; the weaker the ground return the denser the stand.

We experimented extensively with beam divergence and tried the most promising models for each. The results indicated that models performed differently when beam divergence was changed. Table 10 shows the variables used and the residual errors for each of the 5 beam divergences. The model used with the 5 mR beam divergence clearly emerged as the most effective. In addition to the number of single return pulses and average maximum amplitude of the ground return (Peak 2), Peak 1, the amplitude ratio, and the area under the canopy portion of the return were each found to contribute significantly to the estimation of crown cover density. According to the tests involving 24 stands for each beam divergence, it appears tht crown cover density can be measured from the laser to within ±15 per cent of the standard, 95 per cent of the time.

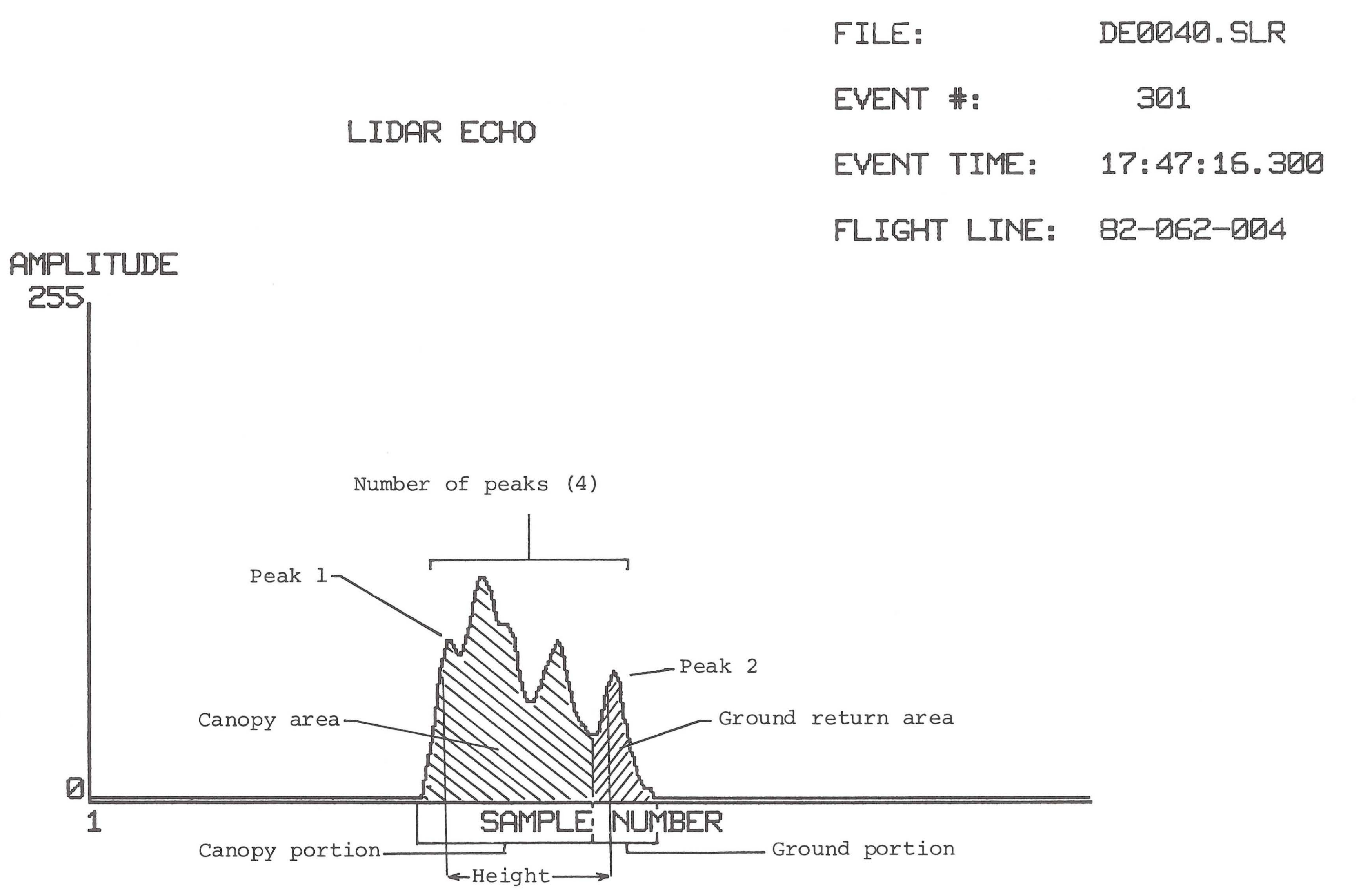


Figure 22. Multiple return event with some of the characteristics used in attempts to estimate crown cover density.

Cover type prediction

The same stands used for developing density regression equations were utilized to test the laser's ability to predict canopy cover type. Along each flight line for each stand the strip corresponding to the laser's footprint was examined by a photo-interpreter and categorized into one of four standard cover type classes:

Class	Description
H	75 to 100 per cent hardwood by crown cover
HS	51 to 75 " " " " " "
SH	26 to 50 " " " " " "
S	0 to 25 " " " " " "

To test the effectiveness of the peak classification algorithm, the laser data were classified according to the four cover-type classes and compared to the frequency distribution of the stand using correlation matrices. One finding was that three-peak pulses were unrelated to cover type. Accordingly, only two-peak returns and returns with more than three peaks were found to be related to the classes. Other variables such as the peak amplitude ratio, the average amplitude of the ground return, and area under the pulse return signature were tested but found ineffective in cover type classification. The best result was obtained from the number-of-peaks variable. Use of this model, nevertheless, produced considerable confusion in the HS and SH mixed classification. Accordingly, these two categories were combined into one, mixedwood, class. Tests of the model on the classfication of stands into three categories resulted in the correct classification about 50 per cent of the time. The best results were achieved with the 10 mR beam divergence setting.

Conclusions from Phase 2

The Phase 2 tests confirmed that the processing of multiple reflections of laser pulses can produce useful forest stand information, particularly height but also, potentially, density and species information. The height and density are known to be related to other quantities such as volume and biomass but such computations were outside the scope of this project. The desirable hardware configuration, flight specifications, and laser signal processing procedures were identified at this point, though some calibration and fine tuning remained.

A wider range of forest conditions concerning species composition, density, hardwood leaves on versus off, and topography were found to have minimal effect on height measurement accuracy. However, beam divergence was found to have a strong impact on the accuracy of hardwood stand height measurements: the wider the beam divergence, the less the systematic and random errors. The accuracy of softwood stand measurements, on the other hand, was not as clearly related to beam divergence. For stand profiling applications, the narrower beam divergences produced better results.

Attempts to modify the production laser such that return pulse signatures could be captured by the CCRS airborne data acquisition system failed because of an improper electronic modification. The plan at this stage was to correct the interfacing problem and repeat the flight test over the local test areas.

The major goal in Phase 2 was to develop methods of producing stand information from a series of individual pulses. To accomplish this a procedure was established which quantified each pulse according to nine potentially interesting criteria. These were based on the characteristics of pulse returns, such as the number peaks, the maximum power (amplitude) of certain peaks, the ratio of maximum power between peak pairs especially including the last peak (the ground return), the area under the curves, and others defined earlier.

The most effective method of estimating stand height was based on classifying multiple-return pulses by the number of peaks, selecting the first and last, and using the 85 per cent leading edge discriminator to extract lapse time between the multiple returns to find height. The average of all valid height readings in a stand was used to yield an estimate of stand height.

The accuracy of such estimates should generally be within ±2 m two-thirds of the time. Higher accuracy levels can be attained by using delimiters to reject the extreme readings of height within a stand, but imposing such rules seemed too arbitrary to suit a general evaluation of pulsed laser. For specific cases, the accuracy, as expressed by RMS, could be reduced to about ±1.5 m by imposing delimiters.

The potential of pulsed laser for stand and terrain profiling was investigated briefly. The profiles shown in Figures 20 and 21 show the possibilities. The actual accuracy of the profiles was not evaluated because the exact vertical position of the aircraft would have to be known. If this can be done with sufficient accuracy, terrain elevation can potentially be accurate to within ±1.0 m in open areas and probably ±3.0 m or better under the forest canopy.

Crown cover density was found to be most effectively estimated using counts of the number of single peak returns, the maximum amplitudes of canopy and ground returns, and the ratio between the two returns and the area under the canopy portion of the pulse return. The best results were obtained using the 5 mR beam divergence but the effect of beam divergence was moderate. Under the best conditions crown cover density of mixed softwoods and hardwoods can be estimated to within ±15 per cent with a 95 per cent level of confidence. The above model was considered the best for the more formal statistical tests to follow.

The forest cover types were best estimated from pulse return data that involved a number of peaks. The use of separate HS and SH categories resulted in considerable confusion. However, if these were combined into one mixedwood class, the classifications were correct about 50 per cent of the time. If the classification had been left to chance, the classifications would have been correct about 33 percent of the time. Therefore our experimental result was not regarded as promising.

The conclusions concerning the use of pulsed laser data to yield estimates of stand heights, crown cover density, and cover type classes were tentative. The purpose of the next phase of the experiment was to confirm these results with more formal statistically designed tests.

Phase 3

THE FORMAL TESTS

The two preceding phases investigated the possibility of generating basic forest survey information from pulsed laser data. The analysis of waveforms of individual pulse returns produced particularly promising results. Procedures for extracting information were developed, tested informally, and further refined or modified as preliminary results indicated. Techniques were developed and tested for producing stand information from runs of many pulses. Several hypotheses concerning the information content of laser data were next postulated and submitted to more formal statistical tests.

Objectives

The most significant information was considered to be the average height of the forest canopy and the prospect of obtaining vertical profiles of stands. Information on crown cover density was also considered fundamental because of its relationship to forest stocking (quantification of the degree to which growing space is occupied). The possbility of extracting some information on species composition was also considered important. Accordingly the following three hypotheses were posed:

1. The average height of the main forest canopy can be obtained from runs of pulsed laser returns such that it agrees with the height measurement made of the same canopies in the field or on large-scale photos to within ±5 m 95 per cent of the time.

It is known that individual trees in a stand can be measured on the ground or on large-scale photos to within ±2 m (95 per cent level) or better (Aldred and Lowe 1978). Stand height averages can usually be estimated to an accuracy of ±3 to 4 m from individual tree measurements. General coverage air photos at a scale of 1:15000 to 1:20000 can be used to estimate stand heights to within ±5 m, provided crown openings permit a view of the ground. Five-metre height classes are about the smallest used in the classification of forest stands for management and operations purposes. These accuracy capabilities and class levels guided the choice of ±5 m as a decision criterion.

2. The average stand density (as expressed in terms of crown cover density) can be placed in 20 per cent classes which agree with air photo interpretations at least 80 per cent of the time.

Twenty per cent classes are the most commonly used for stand classification and mapping, and accordingly, were adopted in this evaluation.

3. The three cover type classes (hardwood, softwood, and mixedwood) can be identified using laser methods such that the results agree with air photo interpretation and/or field observation 80 per cent of the time.

The specific density and cover type classes are defined later.

Procedure

The data collected during the two test flights in the first two phases were divided into two sets: one to be used for the development of procedures and preliminary testing, the second data set reserved only for the evaluation of completed procedures treated next.

Using the reserved test set, the laser tracks were recovered and a series of laser pulse events positioned along the transects. On these transects, segments were defined which covered particular stands. The segments were started and stopped at points where abrupt changes took place with respect to stand height, density, or cover type or where clearly defined features made for easy correlation of laser events with the terrain. Figure 19 illustrated how the transect segments were defined.

The stands were visited in the field and several canopy height measurements made at intervals along the transect segment. The air photo coverage, on which the transect was drawn, was used to locate the transect in the field. The height measurements were averaged to assign stand height to the nearest tenth of a metre.

The crown cover density was measured directly on air photos. The lengths of the transect line falling on live crowns was measured and accumulated for a segment and then expressed as a proportion of the length of the segment (Figure 23) to arrive at per cent crown cover density for the stand. These were placed in one of the following density classes:

Class	Limits (%)	Midpoint (%)
A	0 - 20	10
B	21 - 40	30
C	41 - 60	50
D	61 - 80	70
E	81 - 100	90

The cover type description was completed by photo interpretation and field checking during height measurement. The forest cover types were based on the proportions of softwood and hardwood in stands, according to the following classes and criteria:

Class	Criteria
S	Predominantly softwood (75 per cent or more of the canopy area composed of softwood crowns)
M	Mixed softwood and hardwoods (25 to 75 of the canopy area composed of softwood crowns)
H	Predominantly hardwood (75 per cent or more of the canopy area composed of hardwood crowns)

Many such transect segment (stand) samples were established in order to represent as wide a range of height, density, and cover conditions as possible as well as combinations of these with different beam divergence settings.

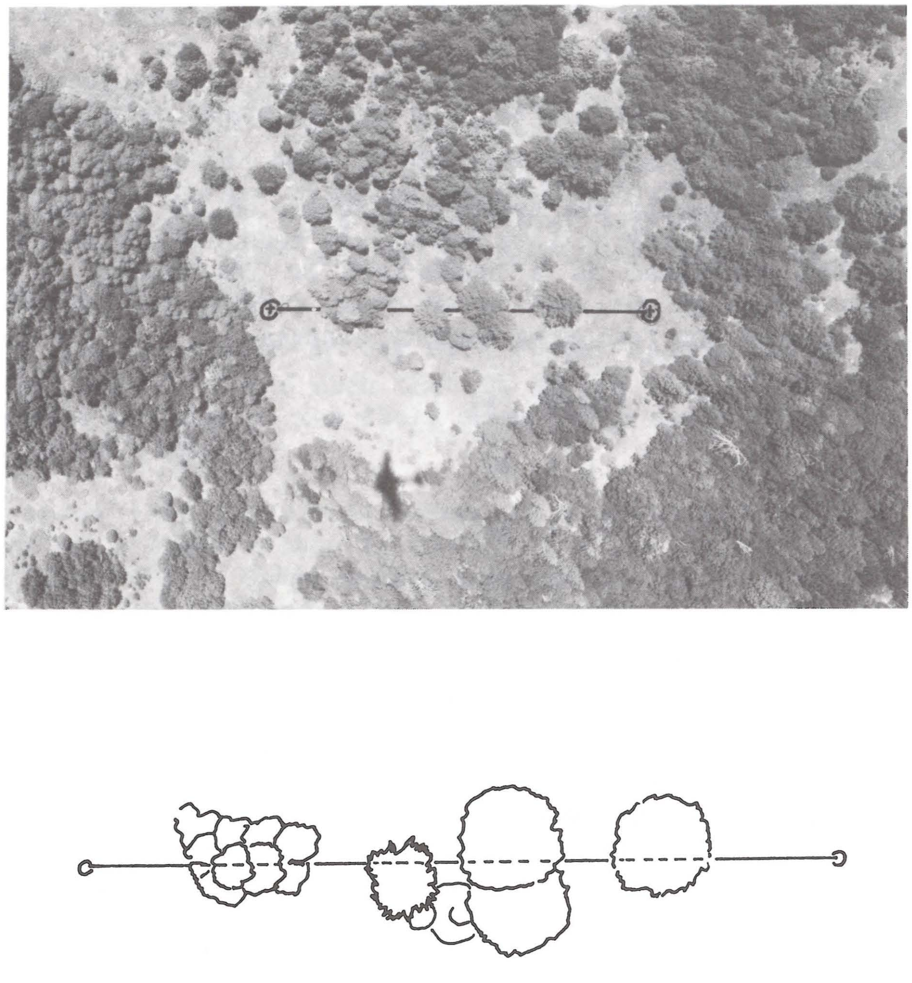


Figure 23. Illustration of how the crown cover density along a sample segment is determined on an air photo. About 50 per cent of the line falls on live tree crowns.

The laser data were then processed through algorithms which, from Phase 2 testing, were concluded to be the most effective in estimating stand height, crown cover density, and cover type.

Analysis and results

Stand height

Stand height was treated as a continuous variable; laser estimates and the field/photo counterpart were treated as paired observations and subjected to linear regression analysis. Regression analysis enabled systematic effects to be identified and quantified, scalar effects to be isolated and, through analysis of residuals, accuracy to be evaluated. The regression model in effect removes systematic and scalar effects, using the assumption that they are constant, and generates corrected height estimates which can be compared to the standard. The systematic and scalar coefficients were derived at the developmental stage in Phase 2 and were incorporated in the stand height model tested in Phase 3.

The stand height algorithm tested used the leading edge discriminator at the 85 per cent level as described in Phase 2. The stand estimate of height was based on the simple average of all readings of height along the segment. The height samples were determined from the first and last peaks of each multiple pulse return. The data were separated by beam divergence but not by cover type. The relationship between the laser estimates of height and the field standard are illustrated in Figure 18. After an adjustment for an average systematic error, the residual systematic errors as expressed by the mean of difference and the variation expressed by the standard deviation of the differences are shown for five beam convergences in Table 10. The root mean square (RMS) was also included to reflect the combined effect of residual systematic and random measurement errors. Somewhat more accurate results were obtained for the wider beam divergences; at the 20 mR setting the RMS error dropped to 2.1 m. This was the equivalent of an accuracy of ±4.1 m at the 95 per cent level, a higher level of accuracy than the minimum requirement.

Crown cover density

The crown cover density was estimated using the variables and model described and tested in Phase 2. The model used the following variables derived from a series of pulse returns occurring on a relatively homogeneous stand: number of single-peaked pulses expressed as a proportion of the total in the stand, the average maximum peak power of canopy returns and ground returns, the average of the ratio of the canopy and ground power, and the average area under the canopy portion of pulse returns. The model which worked the best in Phase 2 was applied to the test data, consisting of 61 stands ranging in crown cover density from 10 to 100 per cent. The results of laser estimates of crown cover density were compared to crown cover density determined photogrammetrically, following the method described in Phase 2 by using a correlation matrix with 20 per cent classes (Table 11). The two methods of placing crown cover density estimates in 20 per cent classes agreed 62 per cent of the time (that is, were on the diagonal shown in heavier lines). This result is not at the level called for as a minimum requirement but the classification of crown cover density using pulsed laser data was, nevertheless, considered to be good. Eighty-nine per cent of the stands were correctly classified within one density class of the diagonal. Because the stands were selected through a random process, the five density classes were

Table 10. Accuracy of models using pulsed laser data to estimate crown cover density

Divergence	Variables used in model	R^2	Standard error of regression (%)
1 mR	Missing pulses, Peak 2, Canopy area, Total area, Height	0.80	14.9
2	Missing pulses, Peak 1, Peak 2, Number of peaks, Total area	0.66	18.1
5	Missing pulses, Peak 1, Peak 2, Amplitude ratio, Height	0.90	7.5
10	Missing pulses, Peak 1, Peak Amplitude ratio, Height	0.89	9.5
20	Missing pulses, Peak 1, Peak 2, Amplitude ratio, Canopy area	0.84	13.9

Table 11. Accuracy statistics for the estimation of stand height from pulses laser data

Beam divergence (mR)	1	2	5	10	20
Mean differences	-2.1	-1.8	-1.6	-0.1	1.1
Standard deviation of difference	2.3	3.2	2.6	2.4	1.8
Root mean squared	3.1	3.7	3.1	2.4	2.1
Number of observations	24	25	24	24	23

not evenly represented. Stands of 80 to 100 per cent crown cover density were much more abundant than the lesser classes. Thus, by chance, many more stands were selected for testing in the densest class.

Forest cover type

The forest cover type classes were generated from laser variables which involved primarily the number of peaks in a return. The model considered most effective (see Phase 2) was used to classify 120 stands which were also classified by photo interpretation and checks of stands in the field. Three classes were used: hardwood, mixedwood, and softwood based on proportions of crown canopy made up of softwood: hardwood - less than 25 per cent softwood, mixedwood - 25 to 75 per cent softwood, softwood - greater than 75 per cent softwood.

The results of the cover type classification are shown in Table 12. Only 38 per cent of the estimates agree, not much better than chance (33 per cent). This result was far short of the minimum requirement and was considered an application of pulsed laser which failed. The test was, however, based on data collected with hardwood leaves on. The leaf-off condition would have worked better but, of course, air photos can be used to delineate such information with minimum effort. This is not the case for leaf-on photography.

Phase 3 conclusions

The purpose of Phase 3 was to evaluate how accurately pulsed lasers can provide stand estimates of height, density, and forest cover type. Minimum standards were set before tests were carried out to establish some guidelines.

The tests established that stand height can be determined from laser data to a higher degree of accuracy than required. Further, species composition and density of stands were found not to affect accuracy appreciably. The Phase 2 investigations also found that beam divergence affects accuracy to a minor extent, the best results being obtained with the 10 mR setting. The wider beam divergence acts to smooth out readings by integrating or "averaging" over a large portion of the stand. This characteristic was considered to not assist stand/terrain profiling because of the greater need to obtain spot elevations.

It was concluded that crown cover density can be measured using laser data, but this measurement fell short of the minimum standard. The evaluation, however, was based on the degree of agreement between laser- and photo-derived estimates of density. Though photo estimates were the best that could be found to establish a test standard, the method itself was subject to minor variability which could be responsible for some lack of agreement.

The classification of forest cover type by laser was thought not to work satisfactorily. A random number generator would do nearly as well.

Table 12. Correlation matrix showing the match of photo and laser derived estimates of crown cover density

	Laser crown cover density					
	10	30	50	70	90	Total
10			1	2		3
30	2	2	2	2	1	9
50			4	1		5
70			1	6	2	9
90			1	8	26	35

Table 13. Correlation matrix showing the degree of agreement between the laser and photo/ground estimates of forest cover type

	Laser estimates of cover type			
	Hardwood	Mixedwood	Softwood	Total
Hardwood	8	35	12	55
Mixedwood	5	32	8	45
Softwood	3	11	6	20

Phase 4

CONCLUSIONS, APPLICATIONS, AND BENEFITS

Summary

1. Pulsed laser technology enabled stand height to be measured accurately, to within ±4.1 m with a 95 per cent confidence. The procedures for extracting height information depended upon processing the waveforms of multiple echoes from individual laser pulses. A series of such pulses was used to provide the stand height estimates.

2. The technology and algorithms for treating multiple pulse returns also enabled crown cover density to be measured accurately. Twenty per cent crown cover density classes were correctly classified by laser 62 per cent of the time and to within one 20 per cent class 89 per cent of the time.

3. Pulsed lasers were found not to provide much information on forest cover type classes (hardwood versus softwood, mixedwood) or other species information.

4. The results of the tests suggested that the ability to penetrate forest cover and to provide a double profile showing both the forest canopy and floor may have considerable promise in ground elevation profiling applications. This application was beyond the scope of this project, because we did not come to grips with the accompanying need to precisely monitor the vertical position of the aircraft during profiling flights.

5. The degree of divergence of the laser beam was not critical to determining stand height. However, the use of narrower beam divergence benefitted stand (and probably terrain) profiling because of the need for accurate spot elevations. On the other hand, stand density classification was improved by the use of wider beam divergence, optimally 5 to 10 mR.

6. The presence or absence of hardwood leaves did not have a significant effect on the use of waveform data in estimating stand height or density.

7. The use of the leading edge discriminators for height determination was optimum approximately at a level 85 per cent of the waveform maximum. The level, however, was not critical; the peaks or 20 per cent level served nearly as well.

8. This project attempted to analyse individual pulses from a much smaller production laser. Technical problems and later unavailability of the CCRS aircraft and the essential ADAS precluded further investigation along this line.

9. The airborne data acquisition system for sampling reflected waveform data, consisting of a transient digitizer and high capacity tape recorders coding events were critical to the production of stand data. Such equipment is highly specialized, complex, and expensive. The possibility of replacing the data acquisition system and waveform data analysis components with a microprocessor-based "black box" designed to generate distance, stand height, and density data directly is extremely attractive. The results of this

project supply most of the specifications required to design and build such a black box.

10. Near-vertical laser distance data from aircraft to forest canopy and the terrain, rather than waveform data, can be used in some instances to provide stand height and density information. However, in dense stands, especially dense hardwoods, the laser may not penetrate the canopy sufficiently often to provide reliable stand data. The rapidly-pulsed production laser was better than the bathymetric laser in this respect, but still not reliable enough where dense canopies and steep or broken topography occur together.

11. The track recovery method based on the use of a bore-sighted video camera and mapping photography, and with time recorded on both media, worked well for the forestry case. The approach can be used as a substitute for, or as a back up to, other navigation systems, such as microwave positioning or inertial navigation systems. The latter are expensive systems and require more hardware and considerable data processing and analysis.

Applications and benefits

As outlined in the foregoing, pulsed lasers provide accurate estimates of stand height and density. The estimates were clearly better than or as good as the readings obtained from photo interpretation of general coverage air photos. The species composition or cover type information from pulsed laser, on the other hand, was not as reliable. The pulsed laser technology was found to penetrate the forest canopy, providing a distance reading to both the canopy, and frequently, the terrain beneath. The stand profiling potential is illustrated in Figures 20 and 21. In the case of hardwood stands about 83 per cent of the readings penetrated to ground level and in the case of softwoods more than 90 per cent. A faster laser pulse cycling rate would improve further the registration of the ground level. Terrain profiling as such was not pursued in this project. However, with a reliable means of measuring the vertical position of aircraft such as by an inertial navigation system, microwave positioning, barometric sensors, or by navigation satellites, terrain profiling to ±3 m or better should be technically feasible, at least in the near future.

Since the accuracy of stand height and density information provided by pulsed laser is as good as that provided by conventional photo interpretation, we could conclude that a comparison should reduce to a cost consideration. In practice this is not likely because photo interpretation involves the delineation and classification of homogeneous areas, whereas the laser, in the configuration tested in this project, samples only along transect lines. Extension or extrapolations outward from these lines is tenuous and therefore should be supported at least by cross transects. Even then a high proportion of an area would remain unsampled. Therefore, for stand classfication, the laser's role is likely to be more effective in conjunction with conventional methods of interpretation. Areas could be delineated on photos and the laser data used to provide, confirm, or check quantitative estimates of stand height and density.

The benefit of the new technology would be in the area of improved reliability of the result and the reduction in effort and cost that the interpreter would incur in completing a stand classification job. More specifically, the amount of field work required to support photo interpretation could be greatly reduced and the quality of the work improved because of the more extensive coverage the laser could offer in place of field checking. The costs of adding the laser technology would involve the elements of setting up airborne and data processing facilities, largely a fixed cost, and the cost of carrying out an airborne mission and processing the results, largely related to the number of line kilometres of transect flown. Since the fixed costs are fairly large at first, cost per line kilometre will decline rapidly as the size of a project increases. Therefore, only large projects will find this technology economical. On the other hand, if a laser profiling service was offered to several potential users, the technology will payoff more quickly because of the economy of scale.

The pulsed laser technology may be profitable in other areas provided additional effort is invested. The possibility of laser terrain profiling in topographic mapping, terrain classification, irrigation and drainage studies, engineering, road and corridor locations, and terrain trafficability were illustrated and touched on in this project. In forestry, variables such as volume and biomass, related as they are to stand height and density, could be computed as efficiently and perhaps with similar accuracy.

The present project was confined to eastern softwood, hardwood, and mixedwood stands. The results are probably applicable as well to the boreal forest covering a large portion of the country. The west coast rainforest, however, where the stands are taller, denser, and sometimes multi-storied were not covered. The tropical forest appears to be a good candidate for laser profiling. Not only are tropical forests often remote and expensive to access on the ground, but stands are very difficult to classify by conventional means. Because of the density and multi-storied nature of tropical stands, height is virtually impossible to estimate. Of course, these same characteristics were a considerable impediment to penetration by radar profilers, and the pulsed laser technology may face similar difficulty. Also, the potential of using multiple return laser data under tropical conditions requires testing and, likely, some revision of the data reduction algorithms.

Recommendations

We think that the following would be good follow-up work to this project:

1. Analysis of laser data should be extended to other forest stand variables such as volume and biomass.

2. Terrain profiling should be pursued. The effort should concentrate not so much on the laser but on the means of tracking the vertical position of the aircraft, an essential requirement. There should be a review of several tracking systems such as inertial navigation, microwave positioning, satellite navigation, the use of barometric sensors, vertical accelerometers, or some combination.

3. The use of the pulsed laser technology for generating forest stand information should be extended to other forest types. The tropical rainforest is a particularly worthwhile investigation. Further tests under tropical conditions should be carried out.

4. A production-oriented forestry system should be designed that would be integrated in one or two compact units. It should be simple to use and would generate forest stand and profile data directly through the use of a self-contained microprocessor. Most data processing specifications for such a system have been established.

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