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Airborne Laser Topographic Mapping Results

Joint NASA/U.S. Army Corps of Engineers experiments indicate the feasibility of meeting stream valley cross-sectional mapping requirements under winter foliage conditions.

Abstract: *The results of terrain mapping experiments utilizing the National Aeronautics and Space Administration (NASA) Airborne Oceanographic Lidar (AOL) over forested areas are presented. The flight tests were conducted as part of a joint NASA/U.S. Army Corps of Engineers (CE) investigation aimed at evaluating the potential of an airborne laser ranging system to provide cross-sectional topographic data on flood plains that are difficult and expensive to survey using conventional techniques. The data described in this paper were obtained in the Wolf River Basin located near Memphis, Tennessee. Results from surveys conducted under winter "leaves off" and summer "leaves on" conditions, aspects of day and night operation, and data obtained from deciduous and coniferous tree types are compared. Data processing techniques are reviewed. Conclusions relative to accuracy and present limitations of the AOL, and airborne lidar systems in general, to terrain mapping over forested areas are discussed.*

Introduction

Topographic mapping (TM) in the U.S. is, at a minimum, a continuing activity. Federal, state, and local agencies that have a need for and are currently engaged in TM are numerous, and their annual budgets for TM more than warrant research and development (R&D) activity to develop more cost-effective means of providing needed data products. Furthermore, many agencies need higher data density to accomplish specific objectives. In other cases, due to budget constraints, agencies are falling behind their required volume of surveying and mapping. Thus, the impetus exists for developing airborne laser technology for application to surveying and mapping.

The results presented herein are from data collected with the NASA Airborne Oceanographic Lidar (AOL) in the profiling mode, the most basic operation of an airborne laser system. Although this mode is cost-effective for certain applications, the ultimate utility of airborne laser technology for TM may be the direct collection of three-dimensional data with a scanning system. Results from analysis of scanning data collected by the AOL will be presented in a later paper, as will details of the potential utilities of an

Photogrammetric Engineering and Remote Sensing,
Vol. 50, No. 6, June 1984, pp. 685-694.
0099-1112/84/5006-0685$02.25/0

airborne lidar system for meeting a variety of other U.S. Army Corps of Engineers (CE) terrain mapping requirements.

BACKGROUND

The AOL was initially conceived and designed to develop, demonstrate, and transfer technology related to various marine applications of an airborne lidar system. The initial field tests of the AOL were performed in the area of laser hydrography. These flight experiments were part of a NASA/Naval Oceanographic Research and Development Activity (NORDA)/National Oceanic and Atmospheric Administration (NOAA) jointly funded interagency program aimed at evaluating the utility of an airborne lidar system for providing high-speed, cost-effective bathymetric surveying. The results of these tests have been previously presented (Hoge *et al.*, 1980; Swift *et al.*, 1981; Guenther *et al.*, 1978) and have been used as inputs to the development of the Hydrographic Airborne Laser Sounder (HALS) system, which is currently in the final stages of development by the Avco Everett Corporation for NORDA (Houck *et al.*, 1981). The utilization of the AOL for performing overland terrain mapping through forested areas, as will be presented herein, is a "spin-off" of the laser hydrography application.

INSTRUMENT DESCRIPTION

The AOL is a state-of-the-art, conically scanning, pulsed laser system designed primarily to perform field demonstration and technology transfer experiments for user agencies needing technology in the areas of airborne bathymetry and laser-induced fluorescence. The AOL operates in either of the two above modes to respectively measure the morphology of coastal waters and adjacent land features and provide for the detection and resolution of oil films, fluorescent dye tracers, water clarity, and organic pigments including chlorophyll (Hoge and Swift, 1980b; 1981a-c). For the above two functions, the AOL system must always perform as a high-precision laser altimeter and thus provide data for the analysis of surface topographic features as well. The timing electronics associated with the altimeter portion of the instrument further allow for depth stratification measurements. These vertical dimension measurements, coupled with the airborne conical scanning capability of the optical portion of the system, allow wide area three-dimensional maps to be produced. Detailed horizontal resolution is provided by the 400 pps real-time data rate capability. The application of the bathymetric mode of the AOL to the determination of tree heights will be explained in the data processing section of this paper. The laser subsystem utilized in this project was eye safe at ranges over 30 m.

The configuration of the electronic portion of the AOL system responsible for the gating and timing of waveform digitization and recording required modification for terrain mapping applications. There are currently 36 analog-to-digital charge digitizers (CD) in the AOL system. These CD's are each 4 ns in width and are separated by 2.5 ns in an overlapping arrangement, yielding a total temporal sampling capability of 90 ns. This provides for a continuous measurement over ~12 m. Because the trees in the various survey sites were determined to generally be between 10 and 22 m in height, an adjustable digital delay was inserted between the bathymetry photomultiplier amplifier and the CD's; this allowed selectivity in the portion of the return waveform to be sampled and recorded. During all of the terrain mapping missions, a delay of 70 ns was maintained. Thus, trees shorter than 10 m or taller than 22 m could not be measured and, consequently, the surface elevation beneath them could not be ascertained. The relatively minor effect of this constraint at the sites we surveyed will be treated further in succeeding sections of this paper.

DESCRIPTION OF THE EXPERIMENT

The field work discussed herein was performed over the Wolf River Basin in western Tennessee. Personnel from the U.S. Army Engineer Waterways Experiment Station (WES) selected flight lines that provided a reasonable assortment of differing relief and vegetation cover. These flight lines are shown in Figure 1 and are labeled 1 to 10. The intent of these experiments was to collect data similar to that which a ground survey team would obtain for input into hydraulic-hydrologic models for simulating stream flow. These lines represent various terrain conditions from smalltown urban to hilly, wooded areas. The flight lines range from about 1.5 to 3 km in length and are generally aligned normal to streams, thus allowing recovery of topographic cross sections of valleys and channels.

GROUND TRUTH DATA

The basic source of ground truth, or comparison data, came by means of photogrammetry. During the same week that the first laser data set was collected, CE Memphis District had aerial photographs of the flight lines made. The location of the lidar ground tracks was determined from 35-mm film ob-

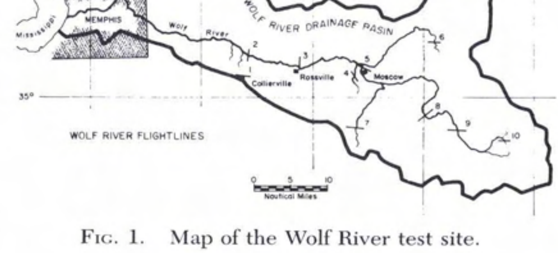

FIG. 1. Map of the Wolf River test site.

tained from the NASA aircraft and were subsequently projected onto the aerial photographs. CE Seattle District provided detailed elevation data along these ground tracks using standard photogrammetric techniques. The photogrammetric data were generally provided in the form of a series of detailed engineering drawings, at a horizontal scale of 1:480, with elevations being given to the nearest 0.1 ft (3 cm). These data were subsequently converted to a computer file of along-track distance versus elevation. In this medium, overlay plots and statistical analyses of photogrammetry and laser data could easily be made. A subset of the ten flight lines flown during the experiment was selected for photogrammetric processing. This subset reflected the most diverse conditions of vegetation and terrain types.

NAVIGATION PROCEDURES

The most difficult aspect of both mission planning and real-time operations was that associated with the navigation of the aircraft over the desired ground tracks. The WES personnel, who are familiar with all of the flight lines, selected ground sites near the ends of the flight lines for tethering helium-filled weather balloons to serve as navigational aids for the NASA pilots. During the missions flown at night, strobe beacons were positioned at these sites. These strobes were as effective as the balloons for guiding the NASA pilots. Generally, the plane passed within 20 to 30 m of the desired ground track.

A photographic record was made on all of the passes flown under daylight conditions with a 35-mm, half-frame flight research camera. A timing slave mounted outside a split lens provided an inset on the upper portion of each frame with a digital display of hours, minutes, and whole seconds. The master timer mounted on the camera controller was synchronized with the AOL master timer prior to each mission, and the timers remained synchronous to within 1 sec during the mission. These serial photographs were later used in conjunction with unique inflections in the laser ranging profile record to recover horizontal control information. A more thorough discussion of this positioning technique has been presented in Krabill *et al.* (1980).

DATA PROCESSING

Aircraft positioning for this application is determined from a combination of velocity, heading, and track angle data from the Inertial Navigation Systems (INS); a minimum of three ground survey points; the AOL range data; and vertical accelerometer data. A straightforward integration process of the vertical accelerometer data, using the ground survey points for control, establishes the aircraft trajectory relative to the survey for the 30- to 60-second duration of a pass (Krabill and Martin, 1982). The aircraft pitch and roll data from the INS and the AOL slant range are then used in conjunction with the trajectory data to calculate the reflecting position of each laser measurement.

Presumably, some of the reflecting positions are on open ground, whereas others are from tree tops or other types of foliage. At this point, the unique time-waveform history recording capability of the AOL, developed for bathymetry (Hoge *et al*, 1980), is utilized. In the bathymetry mode, a pulse is transmitted to the surface of the water, where part of the energy is reflected directly back to the laser receiver. Another part of the energy penetrates the surface, to be reflected back by the bottom, forming a second pulse which is subsequently recorded by the AOL electronics. The time difference between the surface and bottom returns yields a measurement of water depth. An analogous situation exists in the land tracking data over trees, with the forest canopy producing a "surface" return, and the forest floor frequently reflecting a "bottom" return. The sum of the "surface" (canopy) range and the "depth" (tree height) yields a slant range measurement from the aircraft to the ground. Figure 2 illustrates the airborne lidar return waveform in concept. The previously mentioned 70-ns delay is indicated on the figure.

DISCUSSION OF RESULTS

In the graphics references in this section, AOL data, shown in elevation above mean sea level (MSL), are plotted against along-track distance. Vertical scales are exagerated to accent vertical features. In most cases, photogrammetric truthing data are shown superimposed on each of the respective AOL profile records.

Figure 3 is a profile of data obtained over a wooded portion of flight line 9 located on the Wolf

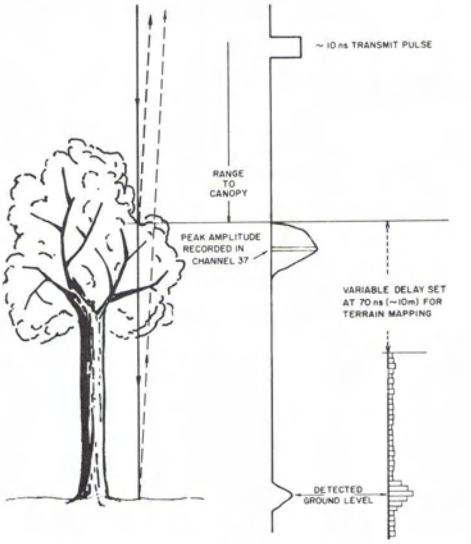

FIG. 2. Concept illustration of laser return waveforms from forest covered terrain.

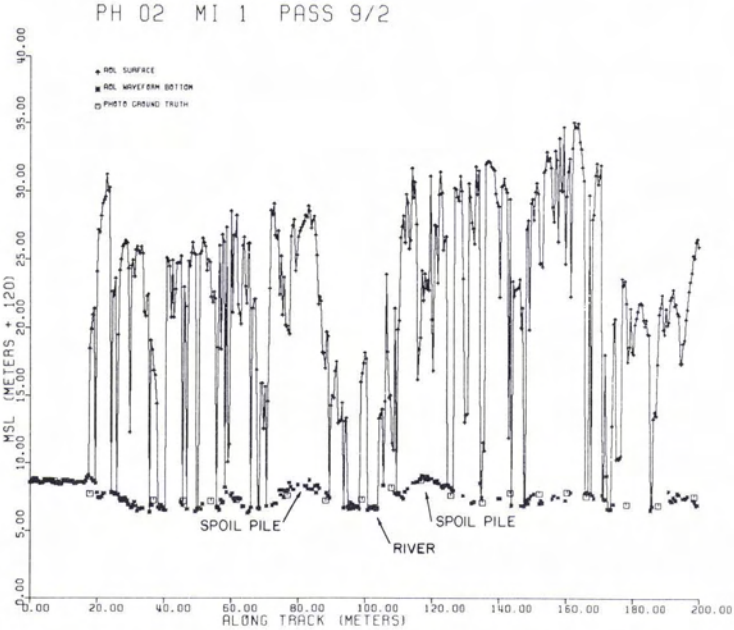

FIG. 3. Cross-sectional profile of Pass 9/2 obtained under winter foliage conditions during March 1979.

River. As can be observed on the profile record, the trees were sufficiently dense to form an almost continuous canopy above the ground surface. For the most part, laser returns of sufficient power to trigger the waveform digitizing system were obtained at or near the uppermost portion of the tree. The individual laser returns from the tree canopy are denoted by symbols given in the figure. A relatively low number of laser pulses were able to entirely penetrate the canopy. Some of these pulses intercepted other portions of a tree or an understory and still others continued to the ground. The ground surface, as determined from the laser pulses penetrating directly to the ground and from temporally recorded laser returns waveforms, is shown for individual pulses by a second symbol in Figure 3 and the photogrammetrically derived ground surface by a third symbol. Ground signals in return laser pulses were obtained for most of the forested portion of the profile except in the vicinity of the river. Near the river, trees were generally shorter than 10 m and fell within the previously discussed 70-ns digital delay; thus, the return waveforms could not be examined for a ground return.

As given in Table 1, penetration over the portion of Pass 9/2 shown in Figure 3 was 39 percent. This percentage calculation was limited to the pulses falling on trees that were between 10 and 22 m in height where determination of ground level was possible. At the 200-pps laser repetition rate and an 85-m/sec aircraft velocity, this amounts to a best case separate elevation measurement approximately

TABLE 1

Flight Line	Pass	Altitude (meters)	Transmitter Divergence (Degrees)	Receiver F.O.V. (Degrees)	Penetration (in percent)	Season/ Time of Day	RMS Difference (centimeters)
6	2	150	5	5	68	W/D	49
6	4	150	5	5	21	S/D	88
9	2	150	3	4	39	W/D	50
9	4	150	5	5	13	S/D	
9	2	300	7	10	30	S/N	
10	2	150	5	5	54*	W/D	
					65**	W/D	
10	5	150	5	5	63*	S/D	
					10**	S/D	

* Coniferous
** Deciduous

every 0.43 m along-track. In forested areas this separation is degraded by the penetration percentage. For example, if we assume a random distribution, the 39 percent foliage penetration cited for Figure 3 would result on the average in a separate elevation measurement every 1.1 m along track.

A quantitative measure of the agreement between the AOL and photogrammetry data sets was determined as follows: (1) after nominal editing, the laser measurements (typically eight) within ± 1.5 m (5 ft) horizontally of each photogrammetry point were averaged; (2) the difference between the average laser value and the associated photogrammetry point was computed; and (3) the root-mean-square (RMS) of all of the differences was then calculated. The RMS agreement between the laser and photogrammetric surveys over the tree covered portion of the flight line was 50 cm whereas agreements of 12 to 27 cm were typically found over open fields along the flight lines. The high spatial sampling density of the AOL profile record affords considerable definition of relatively small perturbations in relief that are difficult to obtain using conventional photogrammetric methods of measurement in wooded areas. As an example, two spoil piles can be seen flanking the stream near the center of the profile in Figure 3. In other records, relatively small-scale features such as ditches, fences, and embankments were also observed.

The results shown for flight line 3 are typical of those obtained on most of the flight lines surveyed during the winter mission. Other examples of winter profiling records are shown in Figures 4 and 5 for flight lines 6 and 10, respectively. Information on the penetration and agreement with photogrammetry for these passes are given in Table 1. The location of the stream bed near the beginning of the cross-section shown for flight line 6 is quite evident in both the laser and photogrammetric records. Flight line 10 contains both deciduous and coniferous trees and will be treated in more detail in the final portion of this section.

WINTER-SUMMER

Differences between results obtained over the various flight lines under winter conditions from those obtained under summer conditions are rather striking but not unexpected. The summer flight tests were conducted primarily to allow full assessment of lidar performance degradation under fully developed foliage conditions. Problems encountered during the summer missions were associated with difficulties in penetrating both upper story and understory foliage.

Comparisons of Figure 3 with Figure 6 and Figure 4 with Figure 7 reveal typical contrasts of winter versus summer airborne lidar survey results. For the summer data (Figures 6 and 7), fewer pulses were able to directly penetrate the canopy, and the resulting ground surface elevations had to be extracted almost entirely from the temporally recorded laser return waveforms. This suggests that a significant portion of the laser energy was spent in the canopy region, and little energy was available to produce returns from the ground; and, indeed, our results showed much lower energy in returns from ground targets. The signal is further dissipated

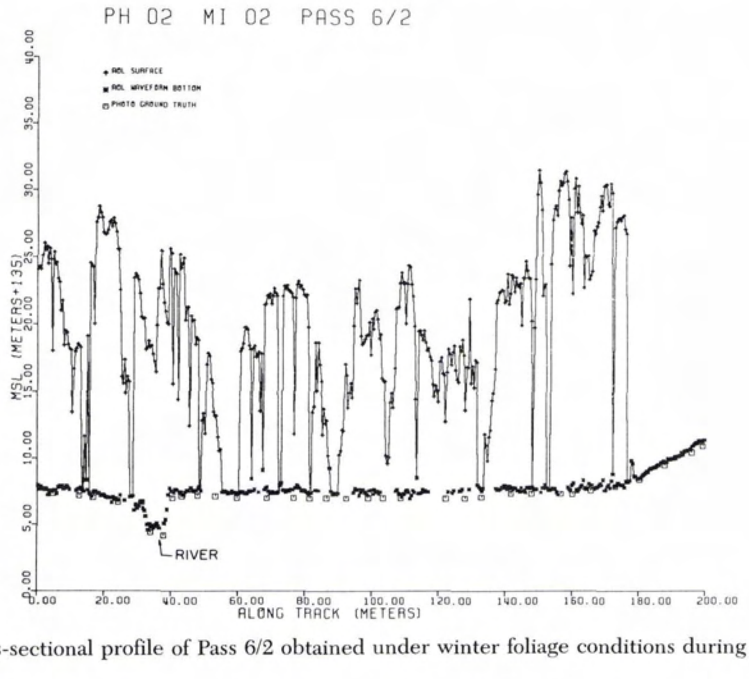

FIG. 4. Cross-sectional profile of Pass 6/2 obtained under winter foliage conditions during March 1979.

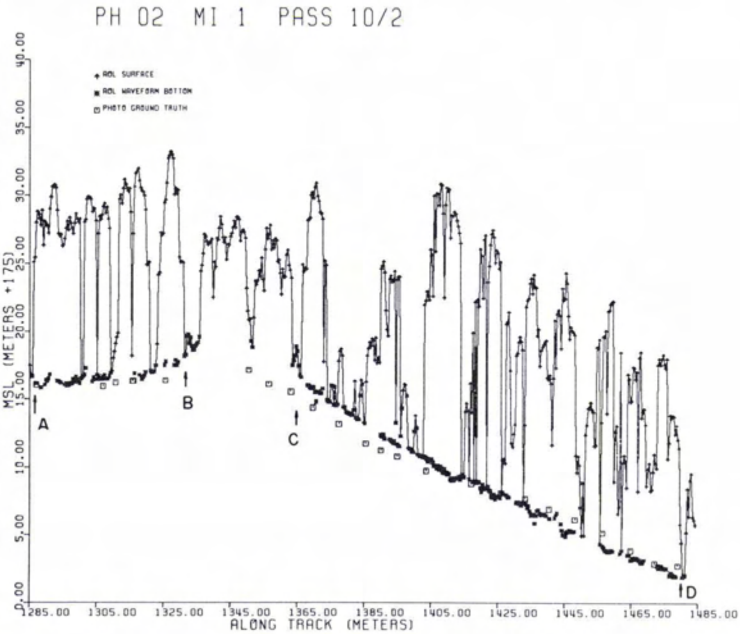

FIG. 5. Cross-sectional profile of Pass 10/2 contrasting differences between coniferous (A-B) and deciduous (C-D) tree types obtained in March 1979.

by absorption and reflection from interfering vegetation in the understory. Finally, return signals from low-lying vegetation occurred rather close in time (and space) to the return signals from the forest floor and often masked the ground return. Thus, low underbrush with foliage can produce returns that are virtually impossible to distinguish from the true ground level.

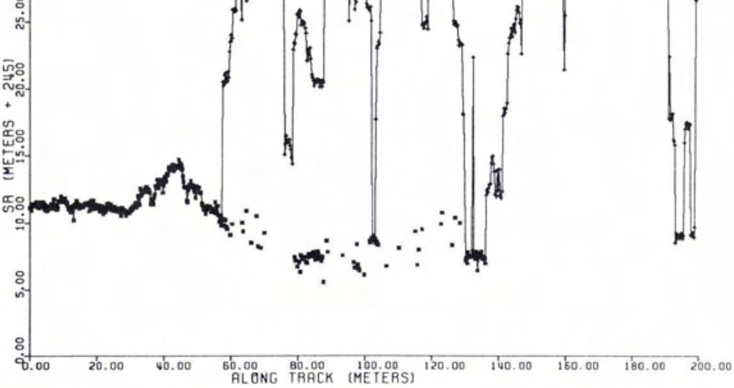

FIG. 6. Cross-sectional profile of Pass 9/4 obtained under summer foliage conditions during September 1980.

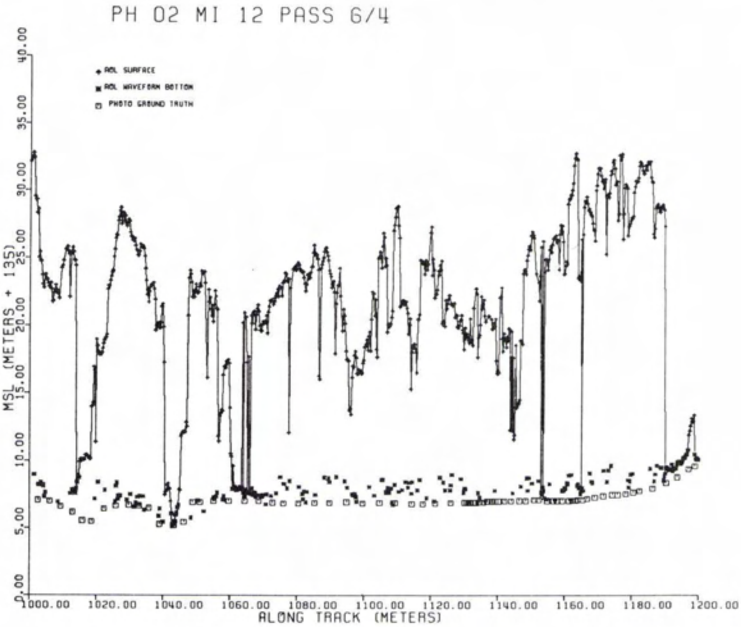

FIG. 7. Cross-sectional profile of Pass 6/4 obtained under summer foliage conditions during September 1980.

DAY-NIGHT

Several of the passes made during the summer 1980 terrain-mapping experiment were re-occupied at night under low ambient light conditions. The night flights were conducted primarily to gauge the utility of additional effective laser power in performing surveys through wooded areas. Although the laser power itself remained at the same level for both the day and night missions, it was possible to remove the interference filter in front of the bathymetry photomultiplier tube (PMT) at night. The narrow bandwidth filter centered at 337.1 nm rejects unwanted background light at other wavelengths during daylight conditions but also reduces the 337.1 nm laser backscattered signal. Additional sensitivity is also obtained under low light conditions from the PMT itself, which is operating under a lowered DC load.

An example of the results from the night mission is shown in Figure 8. Figures 6 and 8 and results of Passes 9/4 and 9/2, which are summarized in Table 1, indicate the typical differences in penetration that were obtained as a result of operating under low light conditions. The positioning of the lidar points during the night mission was somewhat uncertain; thus, direct comparisons with the daytime laser profile or photogrammetric surface are not possible. The results of the night flight investigations suggest that the additional power can yield increased penetration; however, these results are considerably below the performance levels obtained during the winter foliage conditions conducted under daylight conditions. No flights were made at night during the winter 1979 investigations.

DECIDUOUS-CONIFEROUS

The data obtained from the Wolf River test series are somewhat limited for purposes of contrasting lidar performance over deciduous forests with that obtained over coniferous forests. Only a portion of flight line 10 had a stand of pine trees significant enough for use in comparison with deciduous forests. Profiles constructed from the AOL data for winter and summer surveys of flight line 10 are given in Figures 5 and 9, respectively. The section of the profiles containing pine trees is located between "A" and "B" on the figures while the section of the profiles covered with deciduous trees is between "C" and "D".

As can be seen in Figure 5 and in the performance information provided in Table 1, both sections were surveyed quite adequately under winter foliage conditions. The penetration percentages for the two sections of the profile line were 54 and 65 percent for the coniferous and deciduous sections, respectively, for winter conditions. Under summer conditions, shown in Figure 9, the performance over the leafed deciduous portion of the flight line degraded to levels typical of those obtained on the other forested flight lines. The RMS difference between the AOL and photogrammetric profile lines over the pine trees remained at approximately the same level for winter and summer conditions; it

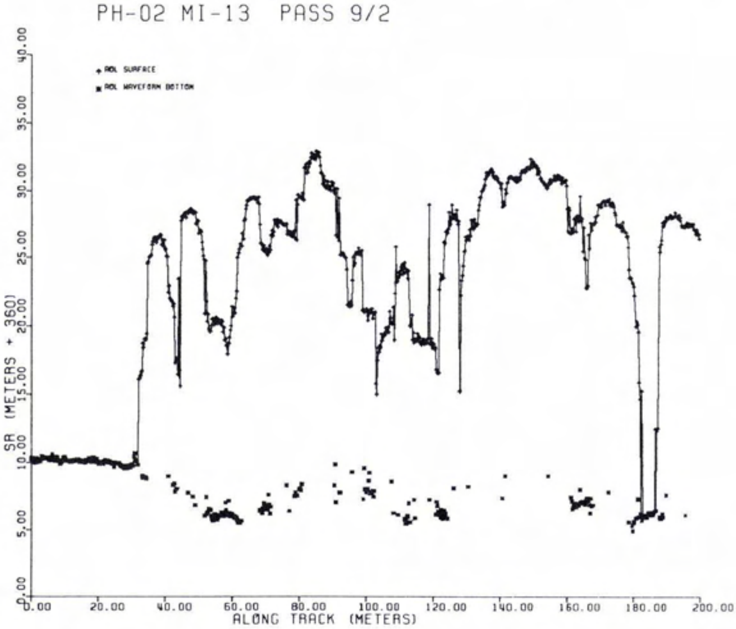

FIG. 8. Cross-sectional profile of Pass 9/2 obtained at night under summer foliage conditions during September 1980.

should be noted, though, that this result is based on a relatively small number of photogrammetrically derived data points. The scatter of surface samples in the AOL summer profile over the pine trees (Figure 9) appears to be somewhat larger than the scatter found in the winter profile (Figure 5); this suggests once more that interference from undergrowth affects the resolution of the return laser

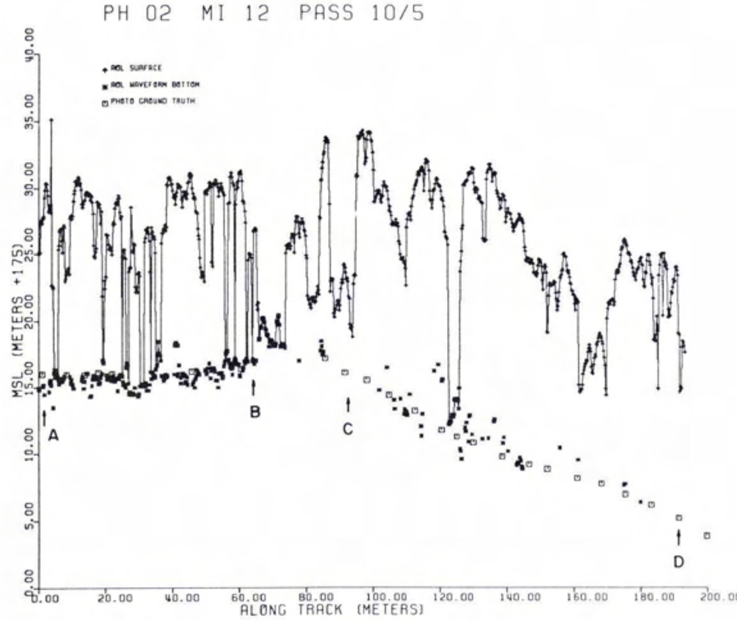

FIG. 9. Cross-sectional profile of Pass 10/5 contrasting differences between coniferous (A-B) and deciduous (C-D) tree types obtained during September 1980.

signal from the ground. Nevertheless, the results indicate that airborne lidar profiling of coniferous forests is not severely degraded by summer foliage conditions, provided the forest floor is not extensively covered by a leafed understory.

Summary and Conclusions

The joint NASA/CE terrain-mapping investigations conducted for the Wolf River Basin were specifically designed to address the potential application of an airborne laser system for meeting CE stream valley cross-sectional mapping requirements. The results from the AOL flights flown during March 1979 under winter foliage conditions were sufficient to show the feasibility of performing airborne laser surveys of the type needed for CE hydraulic and hydrologic modeling. The Wolf River test site was selected because it had been previously studied by WES personnel and because it provided variation in terrain relief, vegetative cover, and cultural use, thus maximizing the extendability of the findings from the experiments. Nonetheless, it is realized that the variations in relief could only be characterized as low to moderate compared to mountainous regions. Furthermore, the diversity of tree types and the degree of development in the forest understory vary considerably from those observed in other sections of the United States. These aspects will require further investigation and analysis.

The rather limited survey conducted over the pine stand on flight line 10 suggests that useful ground surface elevations may be acquired even during summer foliage conditions in areas covered predominantly by coniferous forests. Presently, however, operational surveying of river valley cross sections in deciduous forest areas appears to be primarily restricted to winter foliage conditions for meeting the CE accuracy requirements. The dissipation of the laser signal by a leafed canopy and understory seems to be too severe to permit an accurate assessment of the ground surface in deciduous forests under summer foliage conditions. The results obtained during the night mission flown during summer 1980 indicate that a reasonable increase in effective laser power would still be insufficient for conducting warm weather surveys. However, as advances are made in laser development in the areas of pulse width reduction and increased repetition rate, and as improved digitization becomes available, the prospect for a year-round survey capability with a CE airborne lidar system may improve considerably. Additionally, high repetition rate lasers with a very low beam divergence capability may be able to gather sufficient direct "hits" on the forest carpet to produce adequate ground surface elevations without the necessity of waveform digitization. Indeed, this type of arrangement may be the only straight-forward solution to surveying tropical and subtropical areas with an airborne lidar system.

Of the various aspects of terrain profiling in forest-covered regions addressed in this document, the laser measurement between the aircraft platform and the ground appears to be the closest to operational. Other facets of conducting airborne surveys on a routine basis appear to need further development and improvement. In particular, vertical and horizontal control problems hamper the immediate implementation of airborne lidar surveying. Vertical control, as our results in this study as well as in a subsequent error analysis study (Krabill and Martin, 1982) indicate, can be satisfactorily resolved using an inexpensive vertical accelerometer along with several vertical reference points on each survey line. It is doubtful whether this method can be extended beyond 6 km unless additional vertical reference points are added. Numerous possibilities exist for solving this requirement in a cost-effective manner, including the prospect of utilizing crossing profile lines made by the airborne lidar itself to reduce the number of points needing independent surveying.

Positioning has been accomplished to satisfactory tolerances in this study utilizing a combination of high- and low-altitude aerial photography. The application of this technique, however, is very labor intensive in an otherwise fairly automated processing procedure. Recent improvements in microwave ranging systems or the innovative approaches using pointing laser systems with a surveyed retroreflector field may be able to resolve the positioning problem. The greatest remaining obstacle to the implementation of airborne lidar techniques to terrain profiling over forest-covered areas is the aspect of inflight navigation.

NASA is also currently conducting studies to evaluate the potential of the AOL for providing forest management information from the laser return waveforms. A potential exists for providing biomass density (Hoge *et al.*, in press), tree height (both total and usable stem), and other valuable information. Hardware improvements essential to overland surveying are being implemented. These improvements include finer digitization and resolution, better signal amplification, and a more sensitive PMT. Solutions to the vertical and horizontal control problems are also under consideration.

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(Received 27 July 1982; revised and accepted 23 February 1984)