N O T I C E

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Airborne Laser Topographic Mapping Results from Initial Joint NASA / U. S. Army Corps of Engineers Experiment

W. B. Krabill
J. G. Collins
R. N. Swift
and
M. L. Butler

June 1980
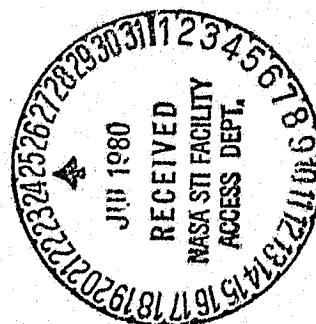
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W. B. Krabill
NASA Wallops Flight Center
Wallops Island, Virginia 23337

J. G. Collins
U. S. Army Corps of Engineers
Waterways Experiment Station
Vicksburg, Mississippi 39180

and

R. N. Swift and M. L. Butler
EG&G/Washington Analytical Services Center, Inc.
Pocomoke City, Maryland 21851

AIRBORNE LASER TOPOGRAPHIC MAPPING RESULTS FROM INITIAL
JOINT NASA/US ARMY CORPS OF ENGINEERS EXPERIMENTS

by

W. B. Krabill
NASA Wallops Flight Center

J. G. Collins
U.S. Army Engineer Waterways Experiment Station

and

R. N. Swift
M. L. Butler
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INTRODUCTION

This document has been prepared to provide information on the current status of the joint NASA/U.S. Army Corps of Engineers (CE) river basin mapping program and the Wallops Flight Center (WFC) Airborne Oceanographic Lidar (AOL) terrain mapping program in general. The second year of activities and analysis of the first year's effort are currently on-going. Although only a portion of the data has received complete analysis, the available results are sufficient to provide insight into the potential utility of an airborne lidar for meeting a host of terrain mapping requirements.

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

The majority of the results presented herein are from data collected 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 from a scanning system, due to the capability of directly collecting three-dimensional data. Therefore, one section of this document will be devoted to preliminary results from scanning data collected by the AOL.

INSTRUMENTATION 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. In performing the above two functions the AOL system must always perform as a high precision laser altimeter, thus allowing the study of topography 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, allows wide area three-dimensional maps to be produced. Detailed horizontal resolution is provided by the 400 pulse per second real-time data rate capability. In the bathymetry mode a short laser pulse is transmitted to the water surface. There the pulse is partially reflected back to the aircraft receiver while the remainder of the pulse continues to the bottom of the water body to also be reflected back to the aircraft. The time spacing of the received pulses allows a determination of the water depth. The study of the amplitude and temporal decay of the pulses allows remote study of sea state and reflectivity, water transmission and/or volume backscatter as well as bottom reflectivity (see Appendix A for a more complete description of the AOL system).

The bathymetric mode of the AOL has been further applied to the determination of tree heights. In this application the tree canopy acts much as the water surface, reflecting a portion of the energy directly back to the aircraft while a part of the energy continues on to the forest floor to be reflected back to the aircraft. The ground level return is subsequently sampled in the same manner as in bathymetry. The separation in the two returns provides a measurement of tree heights and the sum of the initial range to the canopy and the tree height yields an accurate measurement to ground level.

The primary auxiliary instrument which contributed a great deal to the success of this project is a vertical accelerometer. This sensor, although subject to bias and drift over a period of several minutes, is extremely sensitive to short-term vertical motions of

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the aircraft. Long-term motion effects (bias and drift) can be eliminated if three points within the flight line are known. This is accomplished by solving for a quadratic correction (as a function of time), and applying the correction to the doubly integrated accelerometer data, thus providing a vertical reference for the laser data.

Additionally, the aircraft was instrumented with a nadir oriented 35 mm half-frame camera which photographed overlapping scenes, and a nadir oriented TV with a video cassette recorder. A Litton LTN-51 Inertial Navigation System provided aircraft pitch and roll data.

EXPERIMENT DESCRIPTION

The primary data acquisition area for this project was the Wolf River Basin near Memphis, Tennessee. Eleven flight lines were selected by CE Waterways Experiment Station personnel (see Figure 1). These lines represent various terrain conditions from small-town urban to hilly, wooded areas. The flight lines are 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. 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 flowlines of streams.

Demarcation of the beginning and ending points on the flight line was accomplished with red and white weather balloons tethered above tree-top level (20 to 30 m). The NASA pilots were generally able to fly the line to within ± 30 m of the intended ground-track. Typically, four passes were made on each flight line, the first at 300 m (1000 ft) and the remainder at 150 m (500 ft). Various settings in laser beam divergence and fields of view were used to provide data for determining optimum system settings.

Ground truth data came from two sources. First, ground surveys exist from past work conducted in the area by the CE. Unfortunately, none of the laser flight lines came closer than 20-30 meters to these existing survey lines. Thus only a rough comparison of valley and channel cross-section shape can be made from these existing ground surveys. The second source of ground truth, or comparison data, came via photogrammetry. During the same week as the laser data was collected, the CE had aerial photographs of the flight lines made. The location of the lidar ground tracks were determined from the 35 mm film obtained from the NASA C-54 aircraft and were subsequently projected onto the aerial photographs. The CE is also providing detailed elevation data along these ground tracks using standard photogrammetric techniques. To date three of these ground tracks have been received and analyzed.
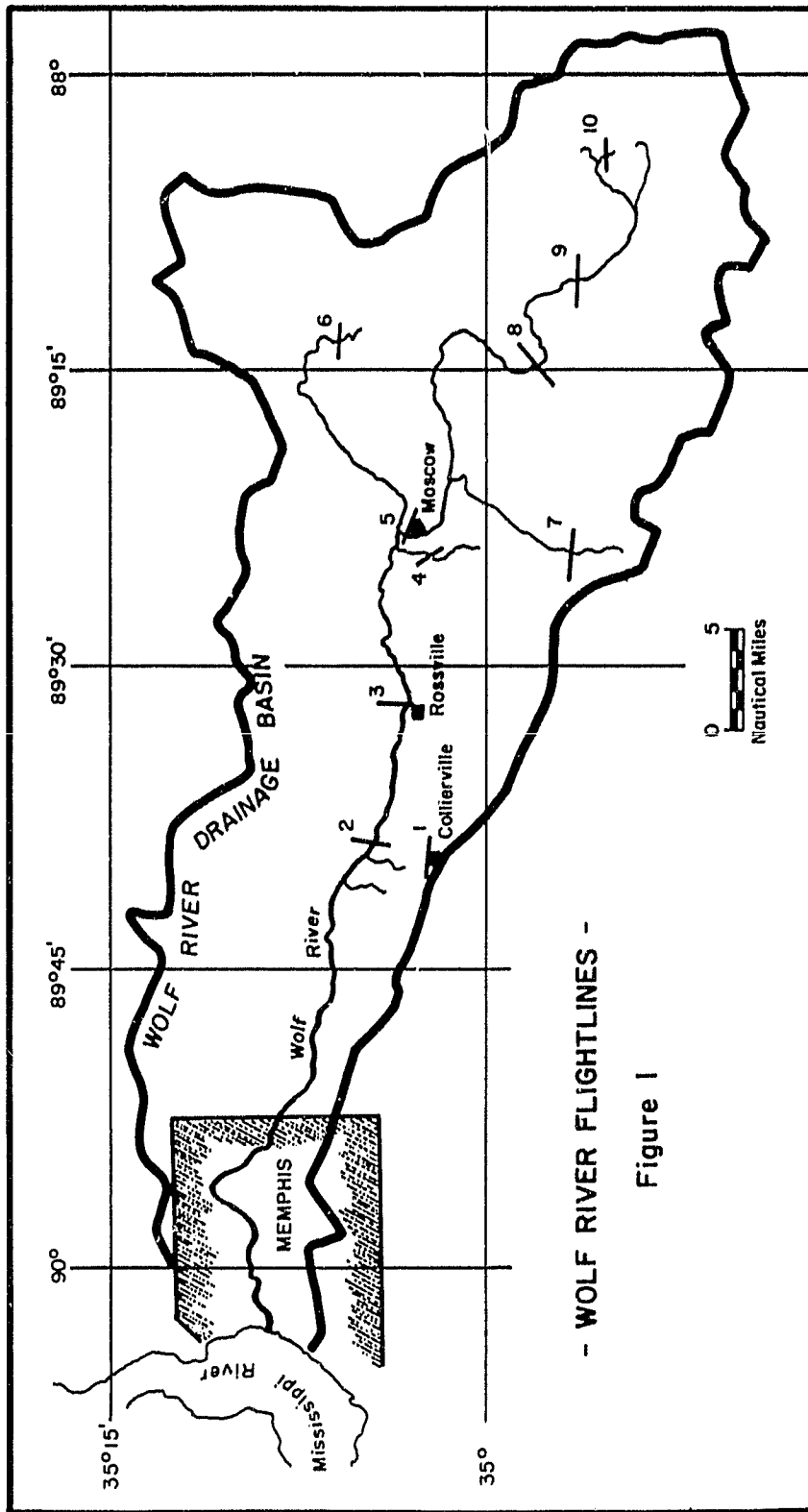
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- WOLF RIVER FLIGHTLINES -

Figure 1

Figure 1. Wolf River flight lines.

COMPARISON OF LASER PROFILE DATA WITH GROUND TRUTH

Photogrammetric data were provided in a series of detailed engineering drawings, at a horizontal scale of 1" = 40', with elevations being given to the nearest 0.1 ft (3 cm); an example is shown in Figure 2. These data were subsequently converted to a computer file of along-track distance vs elevation. In this media, overlay plots and statistical analyses of photogrammetry and laser data could easily be made.

Comparative data for three typical flight lines are presented in Figures 3-10. Some enlarged portions of the data are included to show the quality of agreement. A quantitative measure of the agreement of the two data sets was determined as follows: (1) all of the laser measurements (typically 8) 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. As shown on the figures this comparison to the ground truth indicates an RMS agreement of 12-27 cm (.4-.9 ft) over open ground, and 50 cm (1.6 ft) in forested areas.

SCANNING RESULTS

A number of the flight lines were reflown with the AOL in the scanning mode. Because of AOL system problems (since corrected), the data were collected at a 10° off nadir scan angle and 200 pulses per second (pps), as opposed to the more optimum 15° off nadir and 400 pps. The data from a 150 meter (500 ft) pass on flight line 9 have been processed through a series of algorithms to illustrate the potential capabilities of scanning laser data. Figure 9 is a profile of flight line 9, Figure 11 an aerial photograph of a portion of the flight line, and Figure 12 a computer drawn contour map made from AOL scanning data. Notice that the ground level was successfully extracted from the data in the forested portion of the pass (up to second 7 is over clear land, beyond second 7 is forested). Also, the approximate footprint location of each laser measurement has been projected onto the plot. By following these dots (in a circular fashion) the nature of the conical scan pattern can be observed. Certain portions of the contour lines exhibit a "scalloped" pattern. This slight distortion is largely a sampling artifact resulting from the non-optimum data collection set-up of 200 pps and the 10° off-nadir scan angle. It is expected that 400 pps and 15° off-nadir will minimize this sampling problem.

Quantitative analysis of the complete scan swath would require rigorous comparison with a detailed contour map developed photogrammetrically. Since no contour map of this
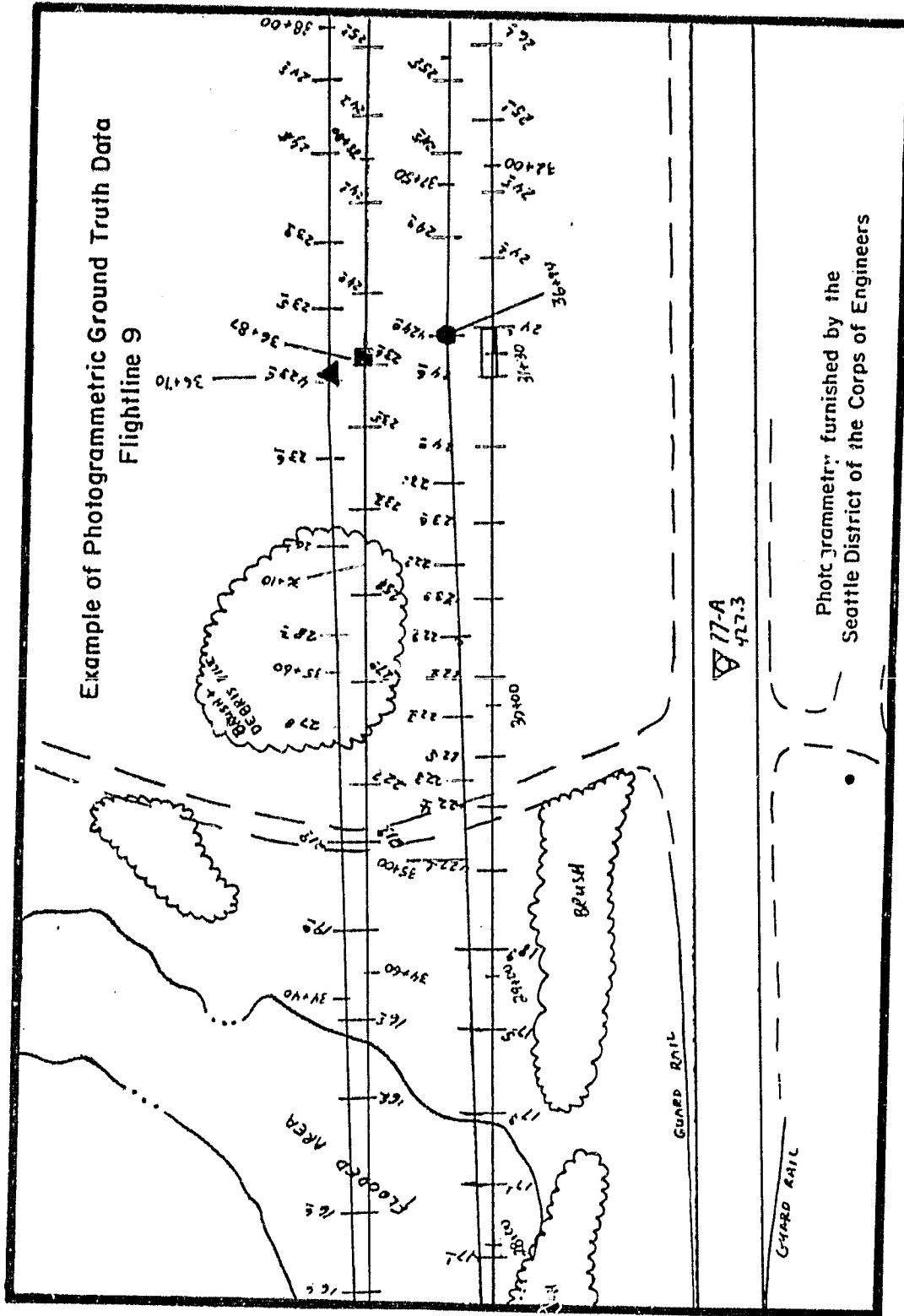
Figure 2. Example of photogrammetric ground truth data.

Comparison of Airborne LASER Survey Line
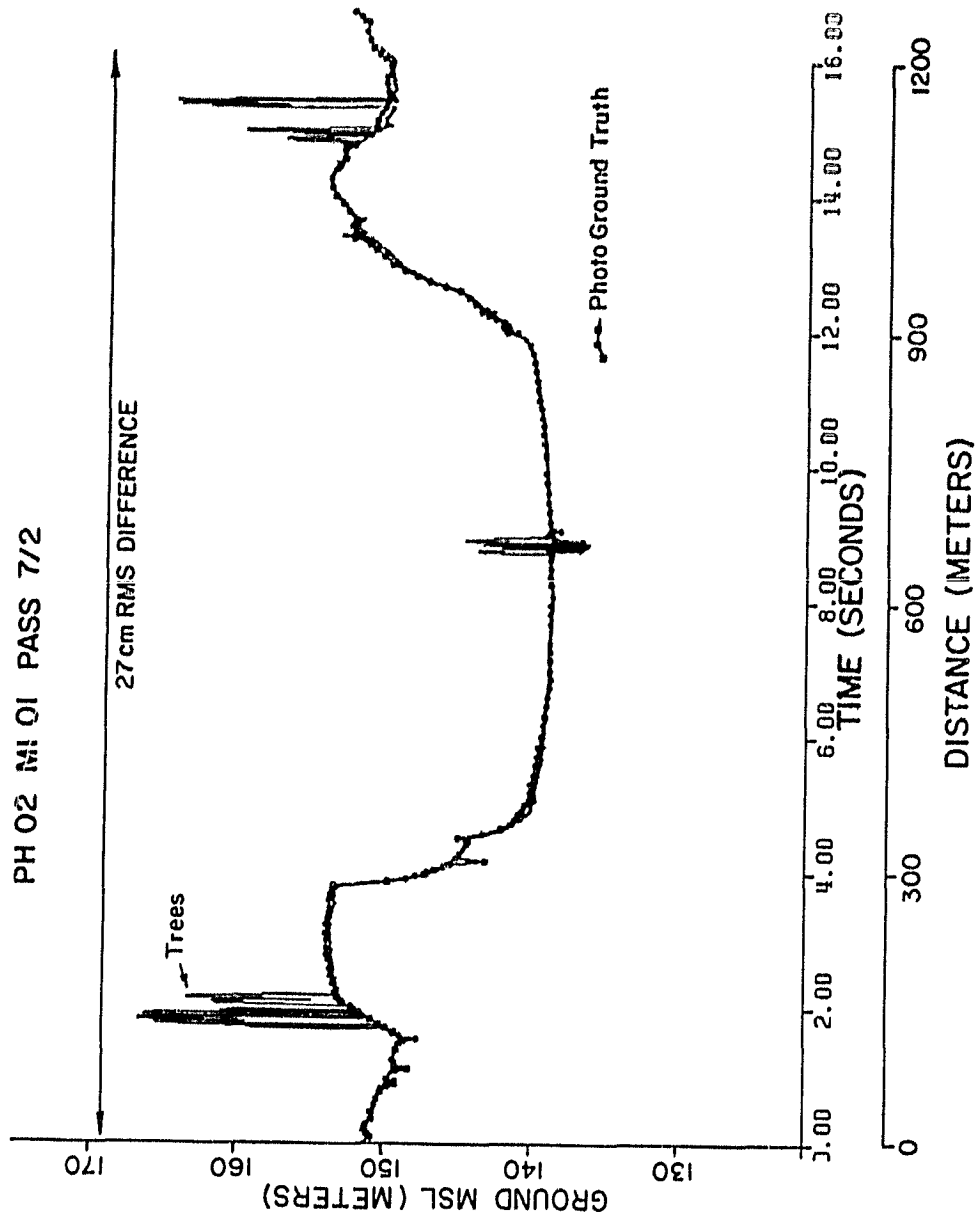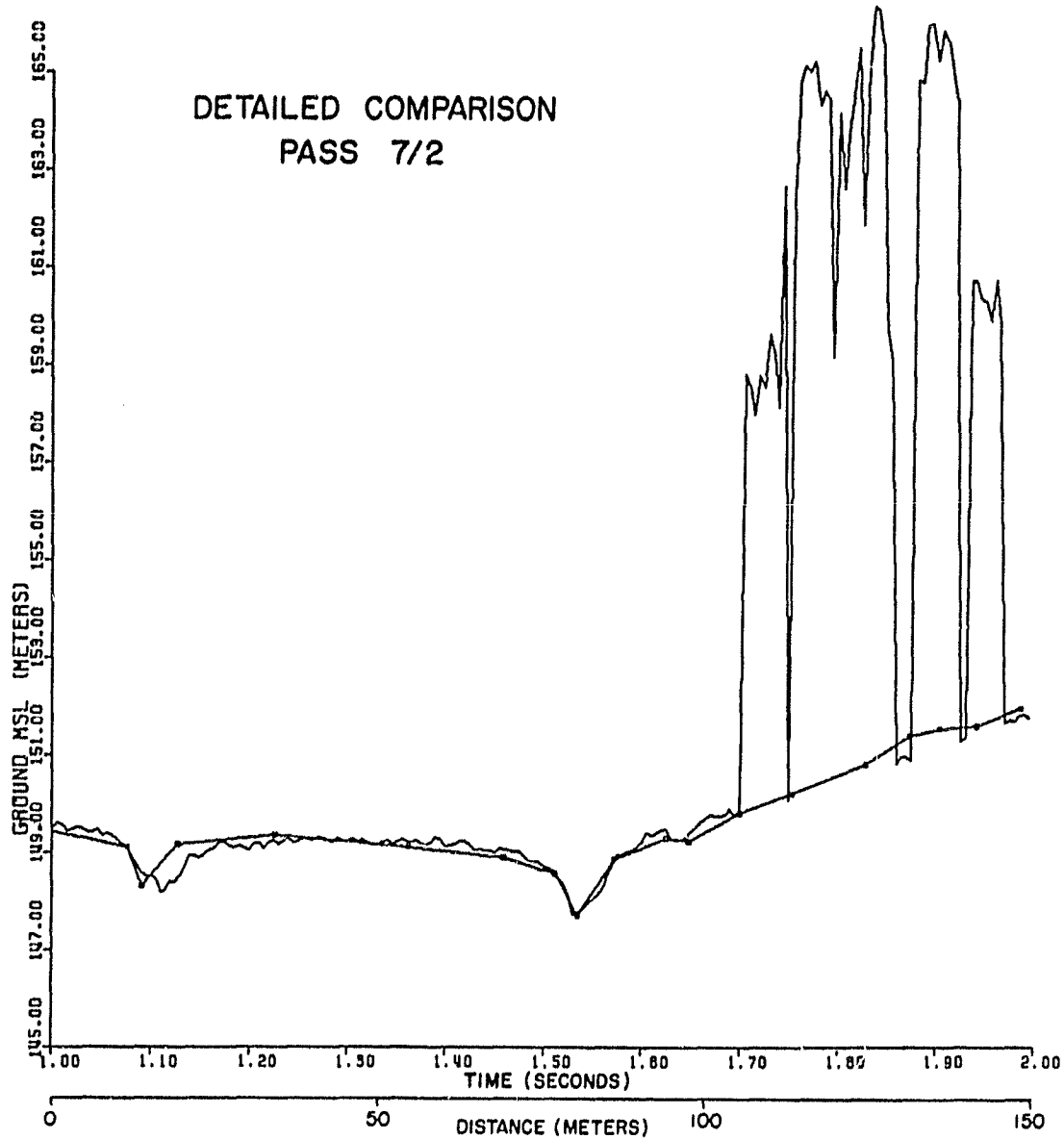with a Photogrammetrically Derived Profile

PH 02 MI 01 PASS 7/2

Figure 3. Comparison of AOL data with ground truth.
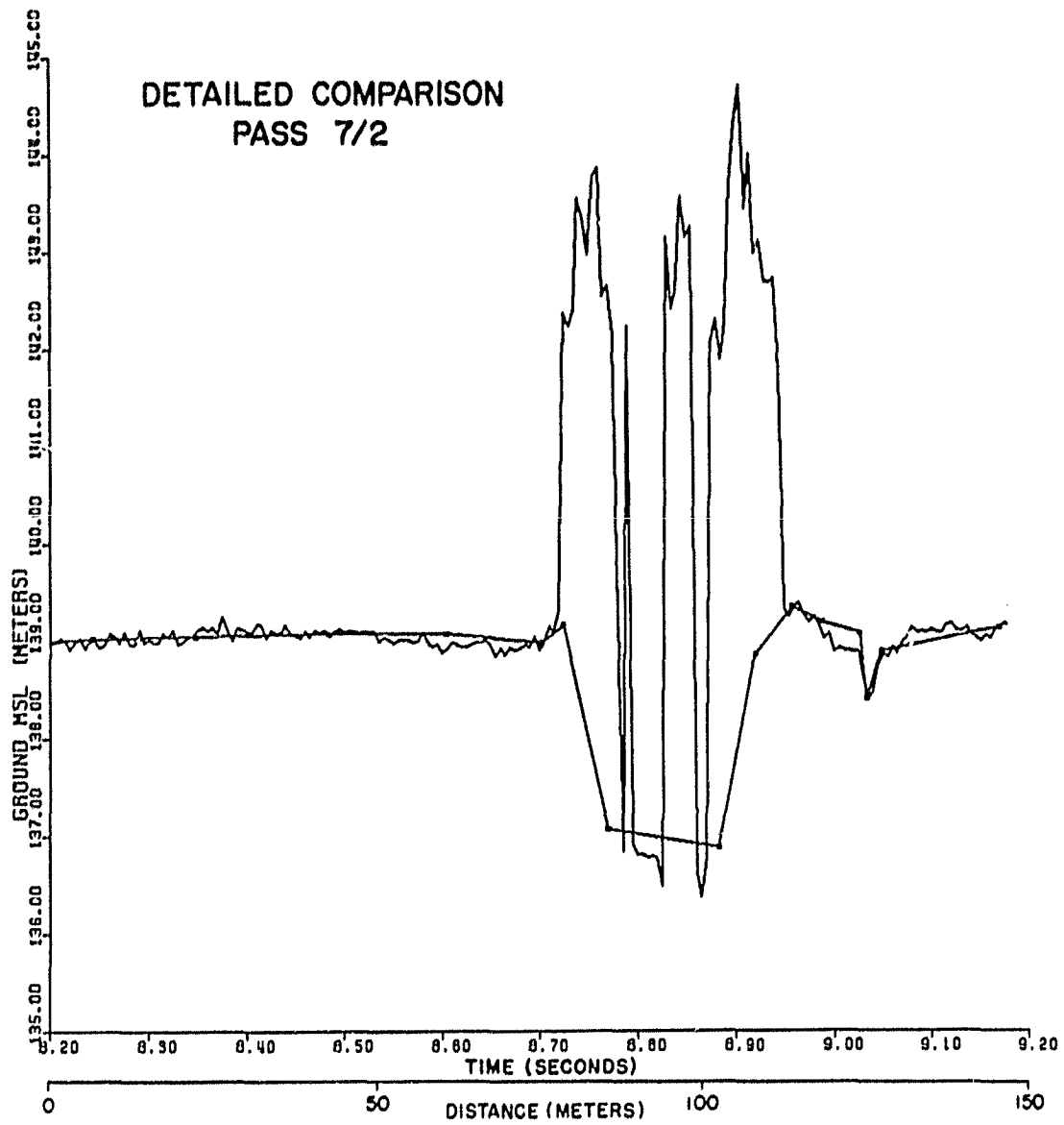
Figure 4.   Comparison of AOL data with ground truth.

Figure 5.   Comparison of AOL data with ground truth.

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Comparison of Airborne LASER Survey Line
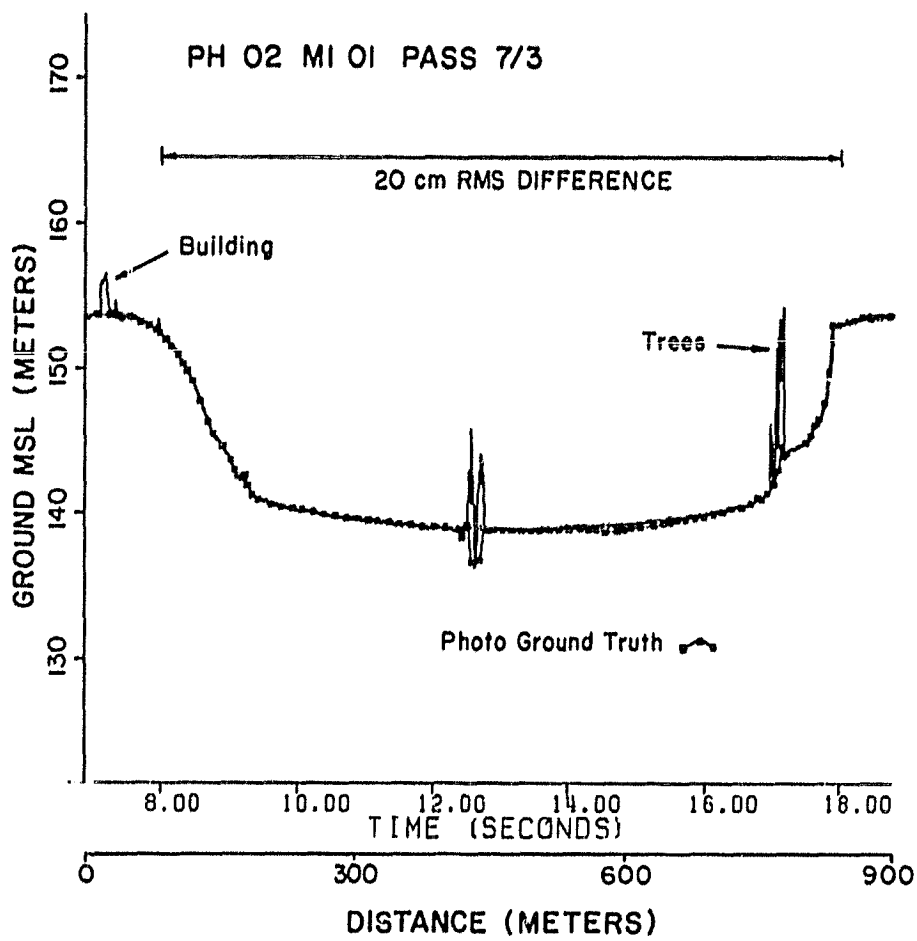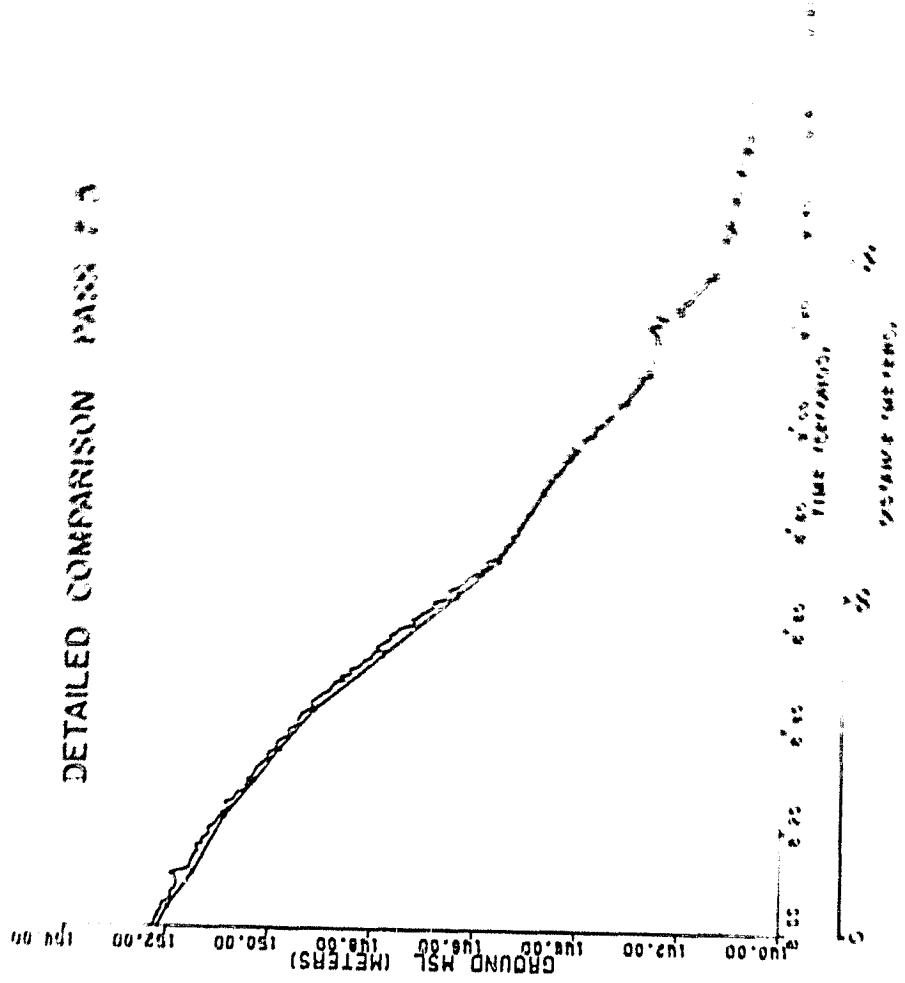## with a Photogrammetrically Derived Profile

Figure 6.   Comparison of AOL data with ground truth.

DETAILED COMPARISON   PASS # 3
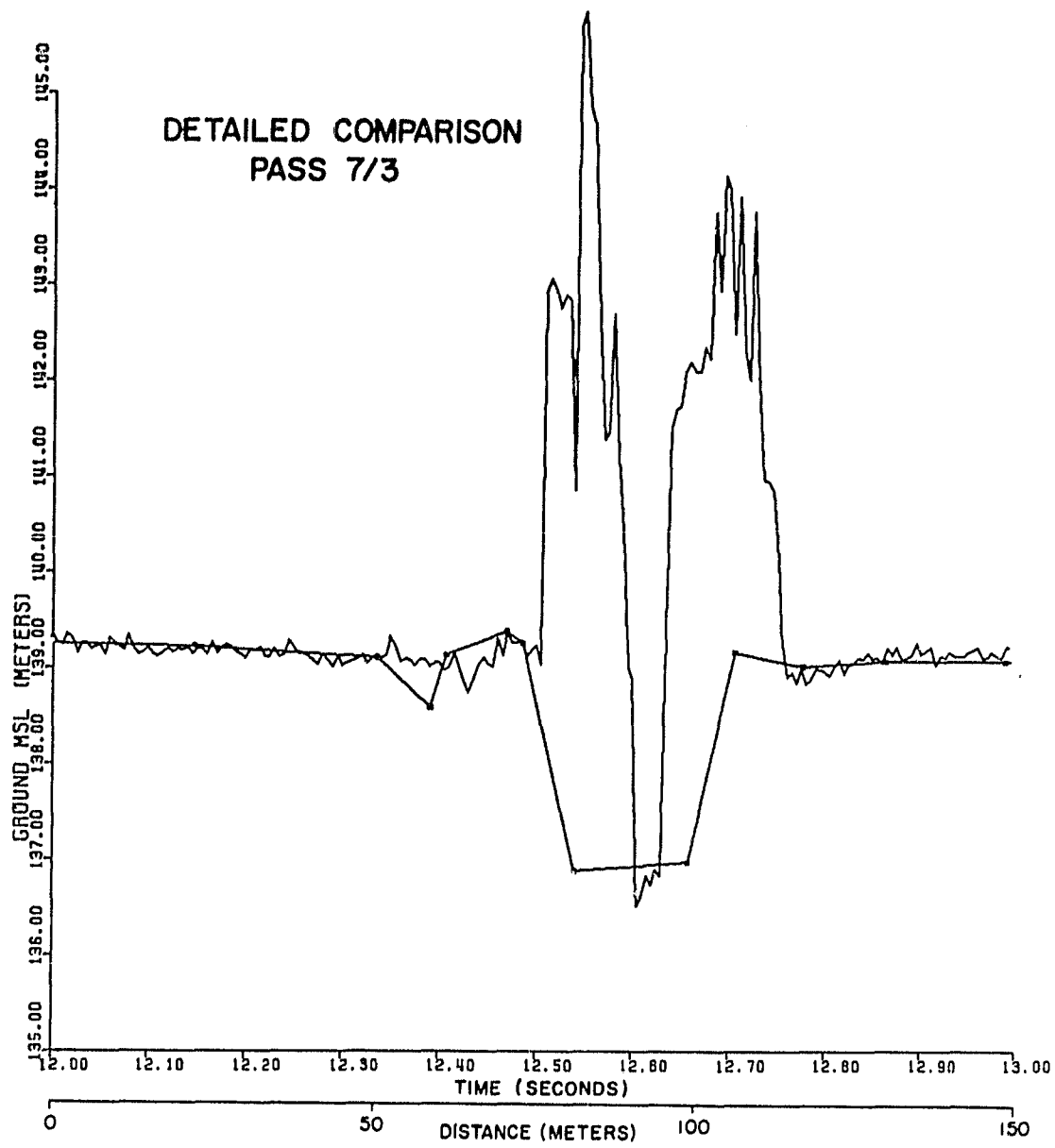
Figure 8. Comparison of AOL data with ground truth.

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Comparison of Airborne LASER Survey Line
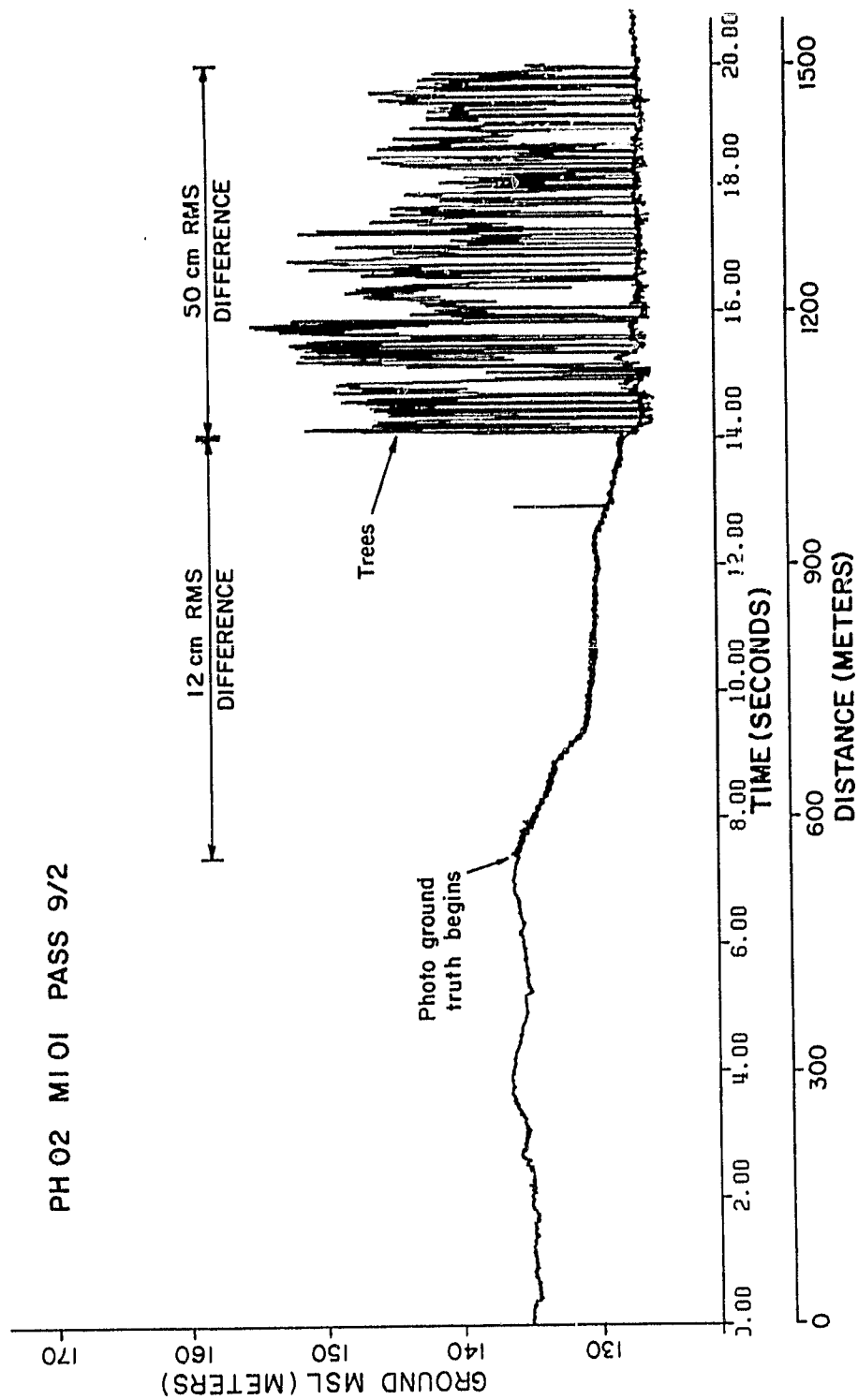with a Photogrammetrically Derived Profile

PH 02   MI 0I   PASS 9/2

Figure 9.   Comparison of AOL data with ground truth.

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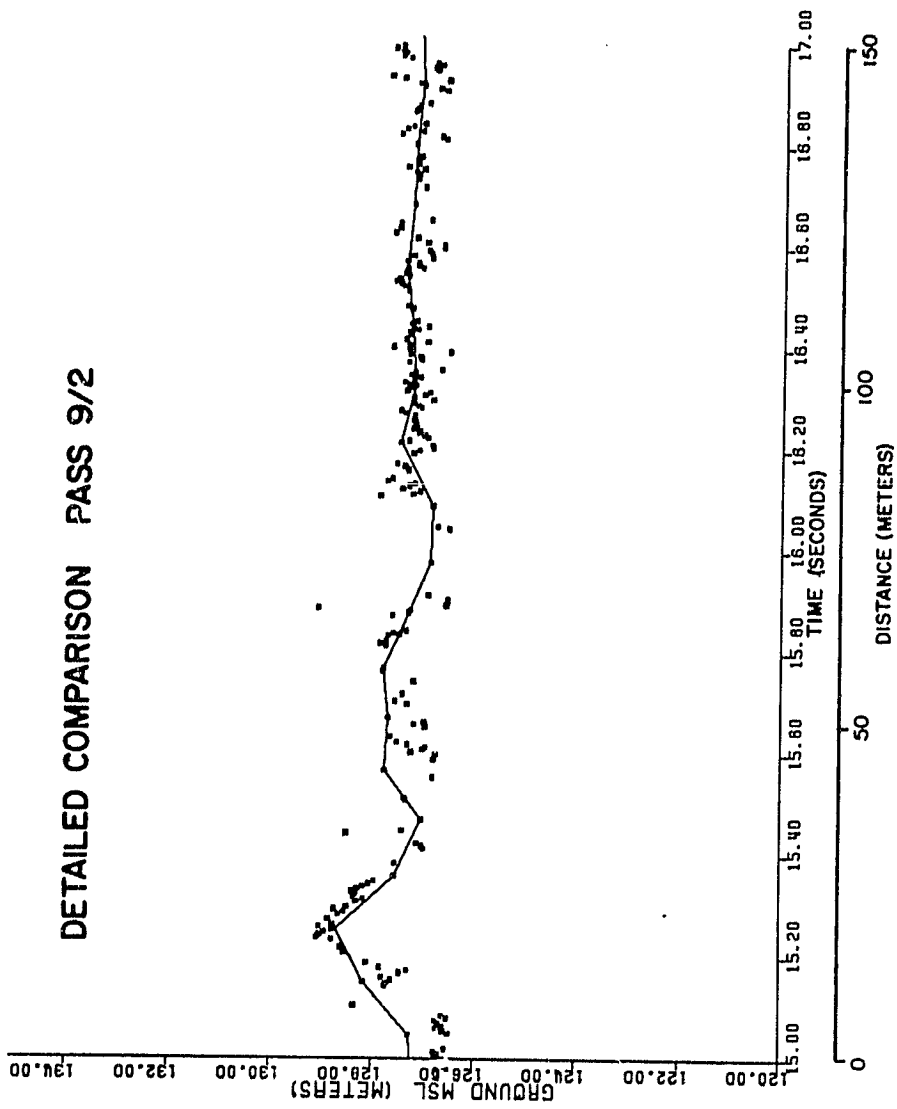
Figure 10. Comparison of AOL data with ground truth.

14
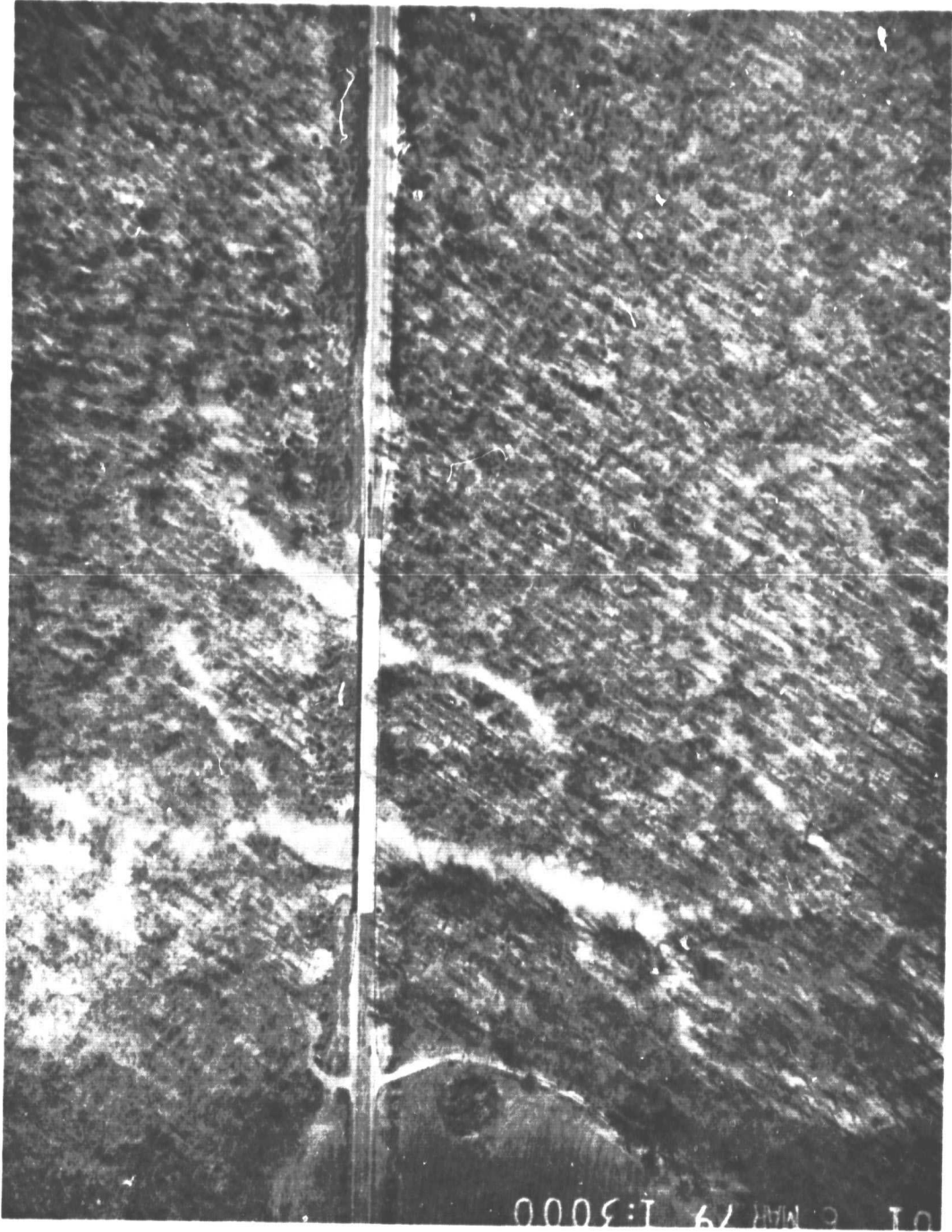
Figure 11. Section of flight line 9.

01 6 MAY 79 1:5000

15

PULSE RATE · 200 pps
OFF-NADIR ANGLE : 10°
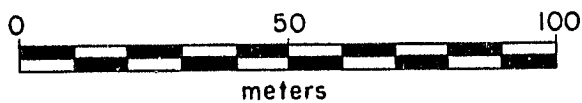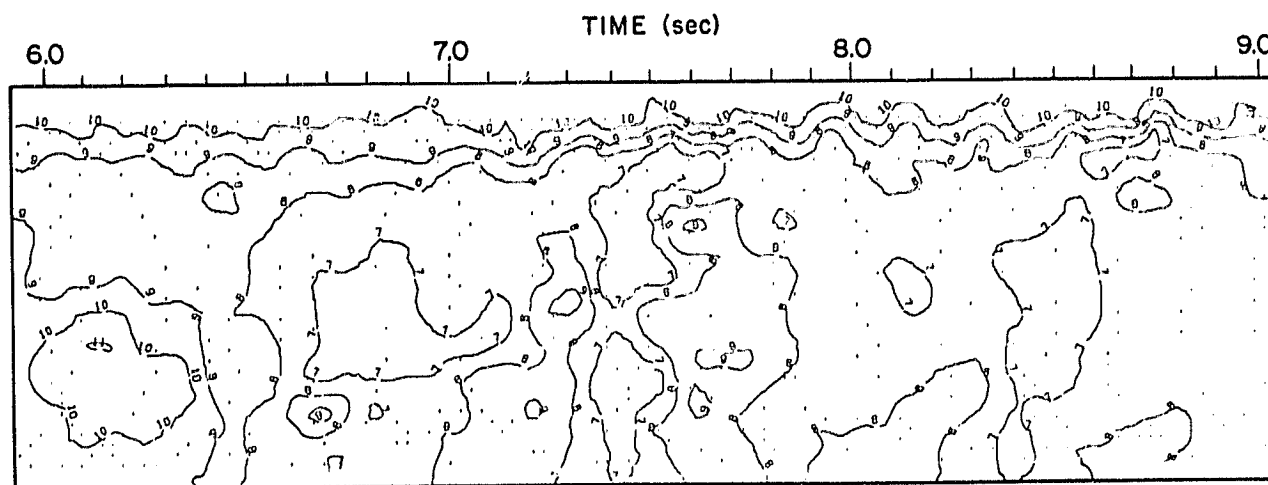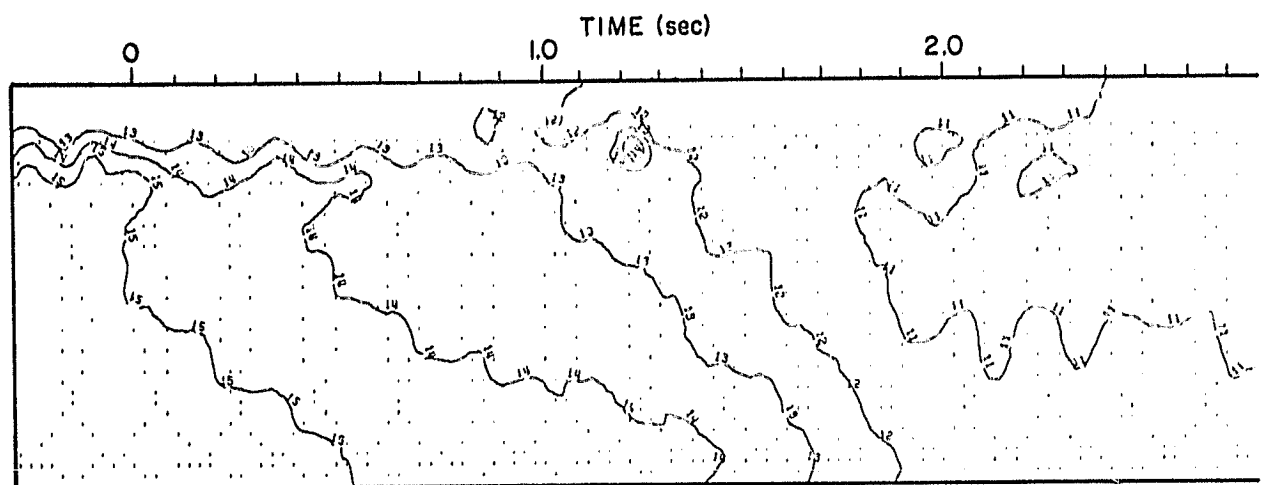
Figure 12.   Contour Map of Flight line 9 from scanning AOL data.

PULSE RATE : 200 pps
OFF-NADIR ANGLE : 10°
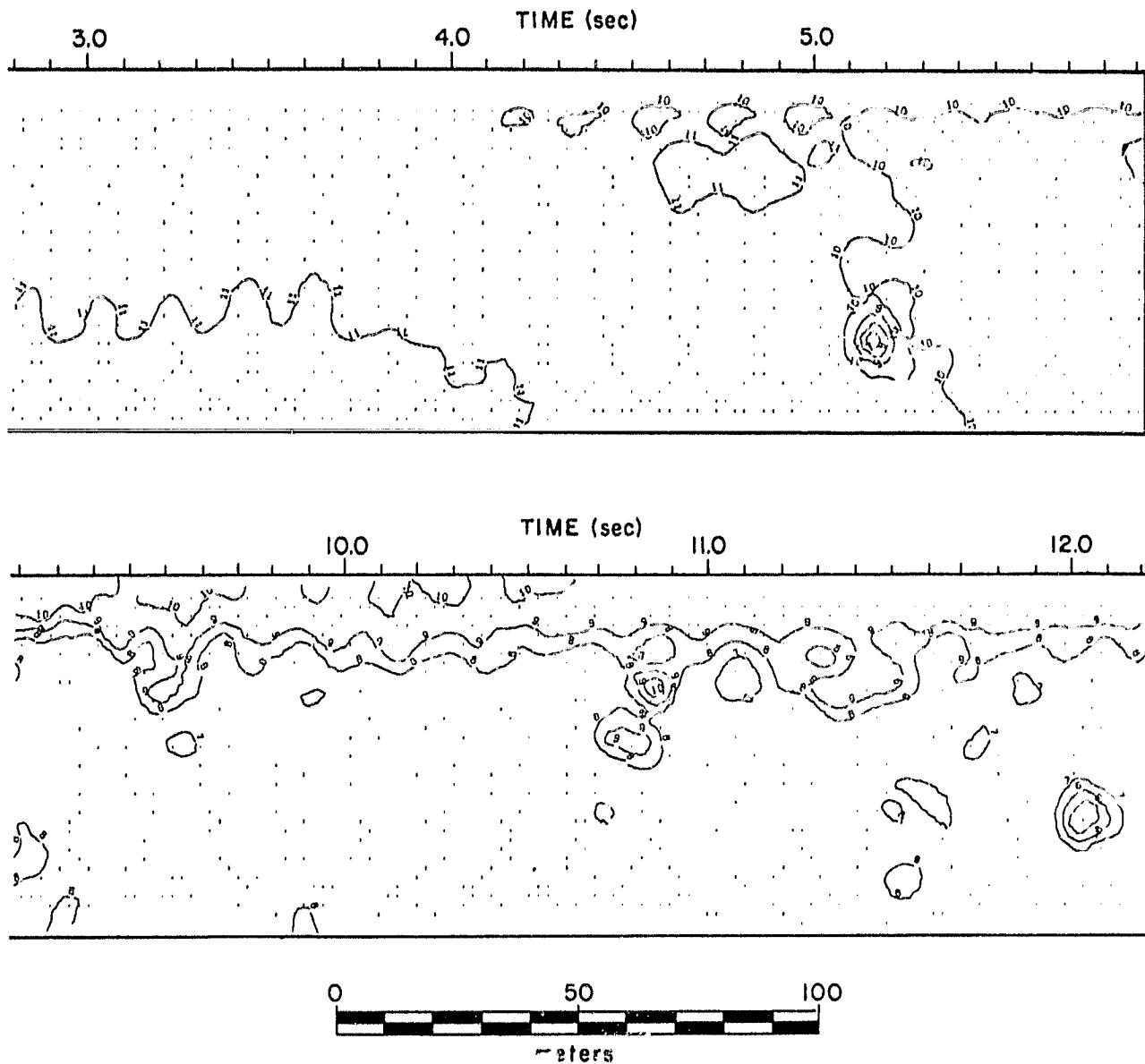
TIME (sec)

3.0   4.0   5.0

TIME (sec)

10.0   11.0   12.0

0   50   100

meters

Figure 12. Contour map of flight line 9 from scanning AOL data.

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type was available only limited portions of the scanning swath could be verified. A comparison has been made to the same photogrammetrically derived profile as is shown in Figure 9. This was accomplished by extracting one column from the digital terrain model (DTM) from which the contour plot in Figure 12 was made. In particular, the column most closely traversing the photogrammetry was chosen. Plots of these two data sets are shown in Figure 13. Because the photogrammetric profile was used as a standard to compare the laser profile pass with (see Figure 9 again), it was compared with the profile line taken from the scanning data. To demonstrate this correspondence, and the capabilities of the laser system, Figure 14 shows: (1) the laser profile data ("+" symbol), (2) the photogrammetry profile (small square), and (3) the extracted profile from the laser scan data (hour glass symbol). Considering the difficulty of exactly fixing the horizontal positions of the data, the correspondence between the two laser sets is considered excellent. It may be noted that the photogrammetric profile fails to show the levee at the left of the stream; this demonstrates the difficulty sometimes encountered in extracting ground surface data in forested areas using photogrammetric techniques.

To further show the capabilities of the scanning data, Figure 15 is a 3-D plot produced from a portion of the DTM shown in Figure 12. To enhance the details within this image, Figure 15 has been augmented by an illustrator to produce Figure 16. A comparison of the photograph (Figure 11) with Figure 16 shows that the essential details of this very difficult area to survey have been mapped by the scanning laser.

A final comparison of the scanning data is shown in Figure 17. This same scanning pass mapped the road surface on the extreme left of the scan swath. The left-most along-track column was extracted from the DTM and plotted together with a ground survey of the road surface. For all practical purposes, the two data sets are the same.

FUTURE EFFORTS

To date all of the 1979 Wolf River data sets have been validated and have received preliminary statistical treatment. The aerial photography and video-tape information from the nadir looking cameras have been reviewed and the ground tracks have been projected onto CE aerial photographs as precisely as possible. The data sets presented herein have received complete analysis and the remainder are currently in various stages of processing. Analysis of all 1979 data sets are expected to be completed by June 1980.

The 1979 field work was performed under early spring conditions when deciduous trees were devoid of leaves, thus making it easier to detect the ground surface in most of the forested areas. Sections of coniferous forests were overflown on some flight lines and the ground surface was resolved through these trees, although the data was noisier.

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PH U2   MI 03   LINE 9 SCAN DATA   (WD # 37)
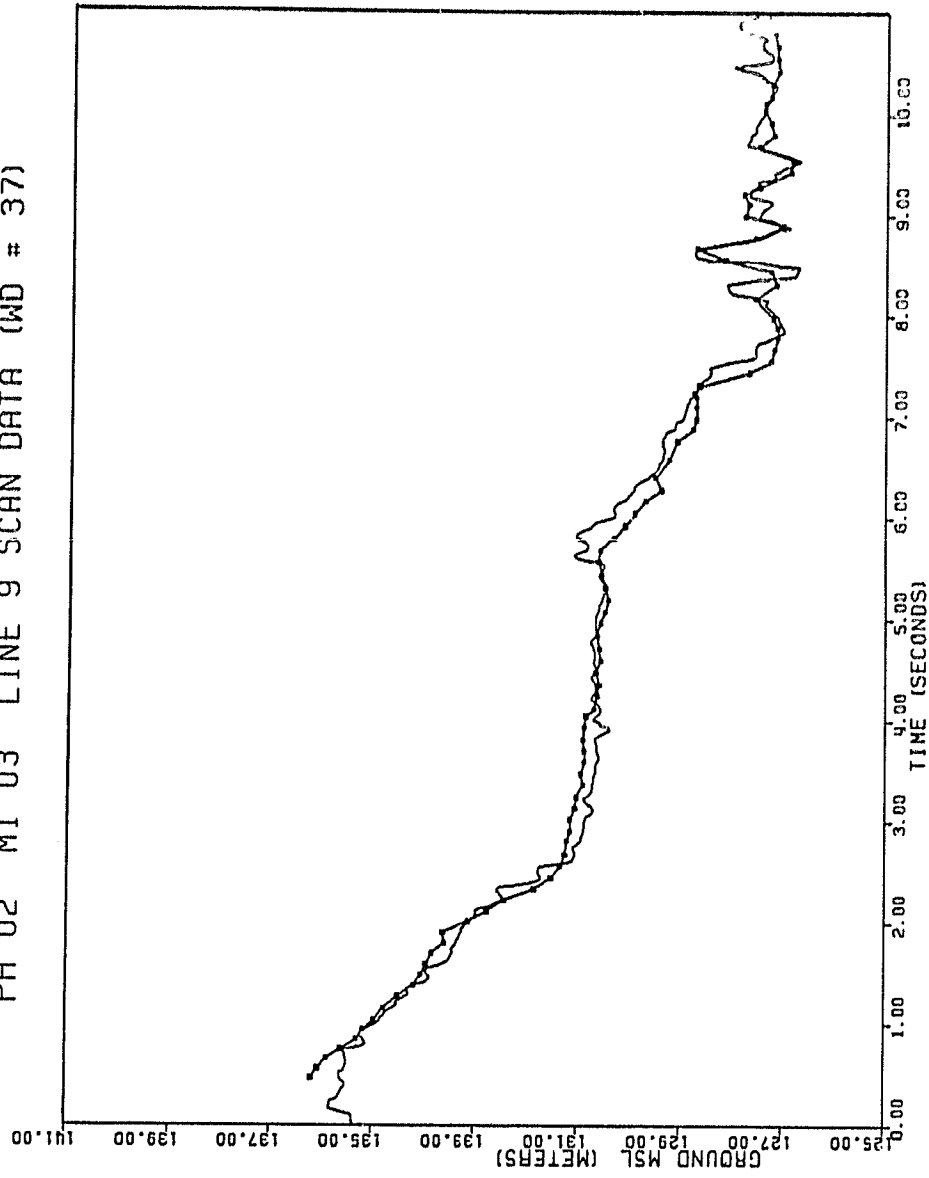
Figure 13.   Comparison of AOL scanning data with ground truth.

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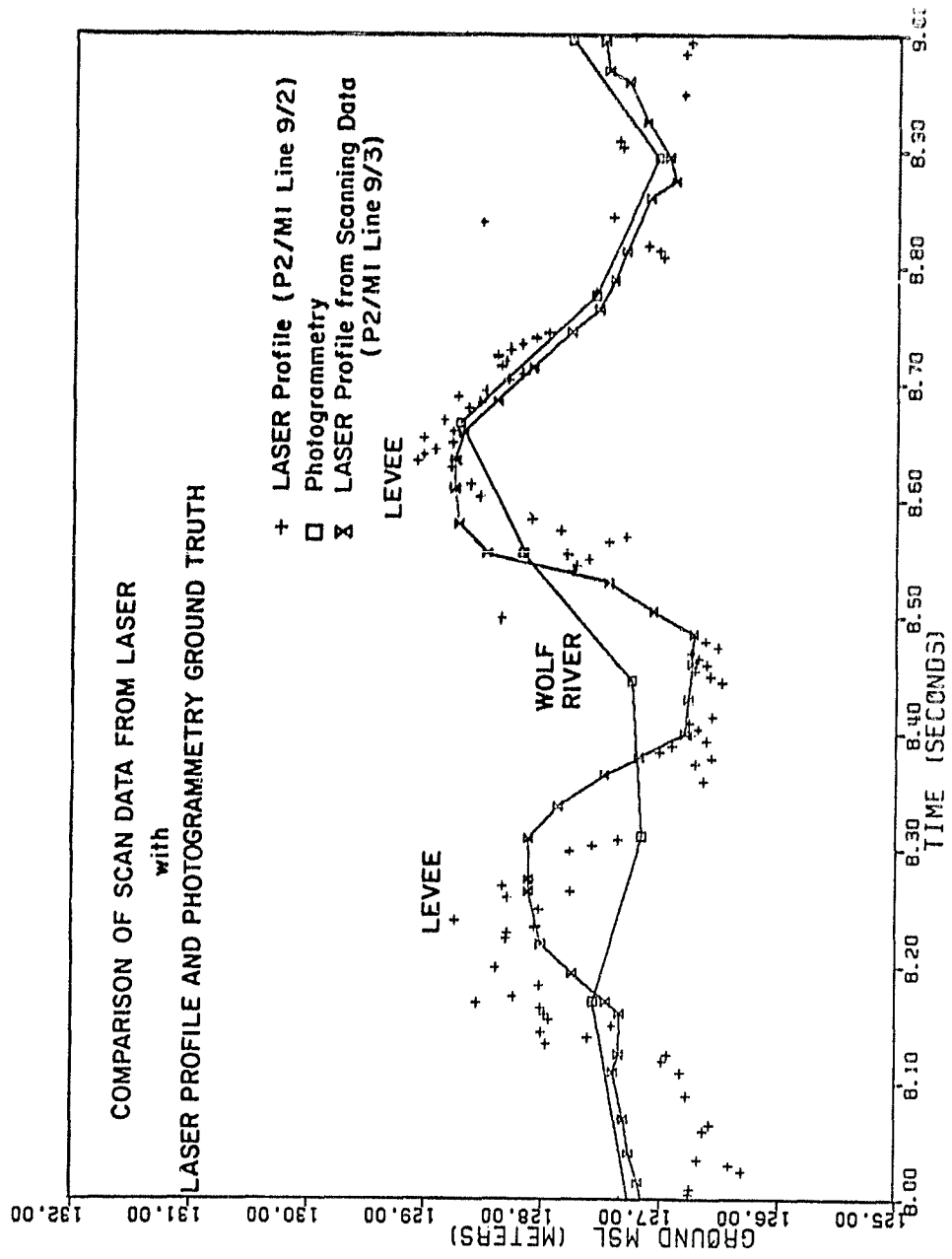
Figure 14. Comparison of AOL scanning data with ground truth.

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Ph 2 Mi 3 Line 9/3
PULSE RATE : 200 pps
OFF-NADIR ANGLE : 10°

Figure 15.   Example of 3-D data product from AOL scanning data.

Ph 2 Mi3 Line 9/3
Pulse Rate: 200 pps
Off - Nadir Angle: 10°

State Rte. 72

50

meters

0

Figure 16. Example of 3-D data product from AOL scanning data.

LINE 9 SCAN DATA & ROAD SURVEY
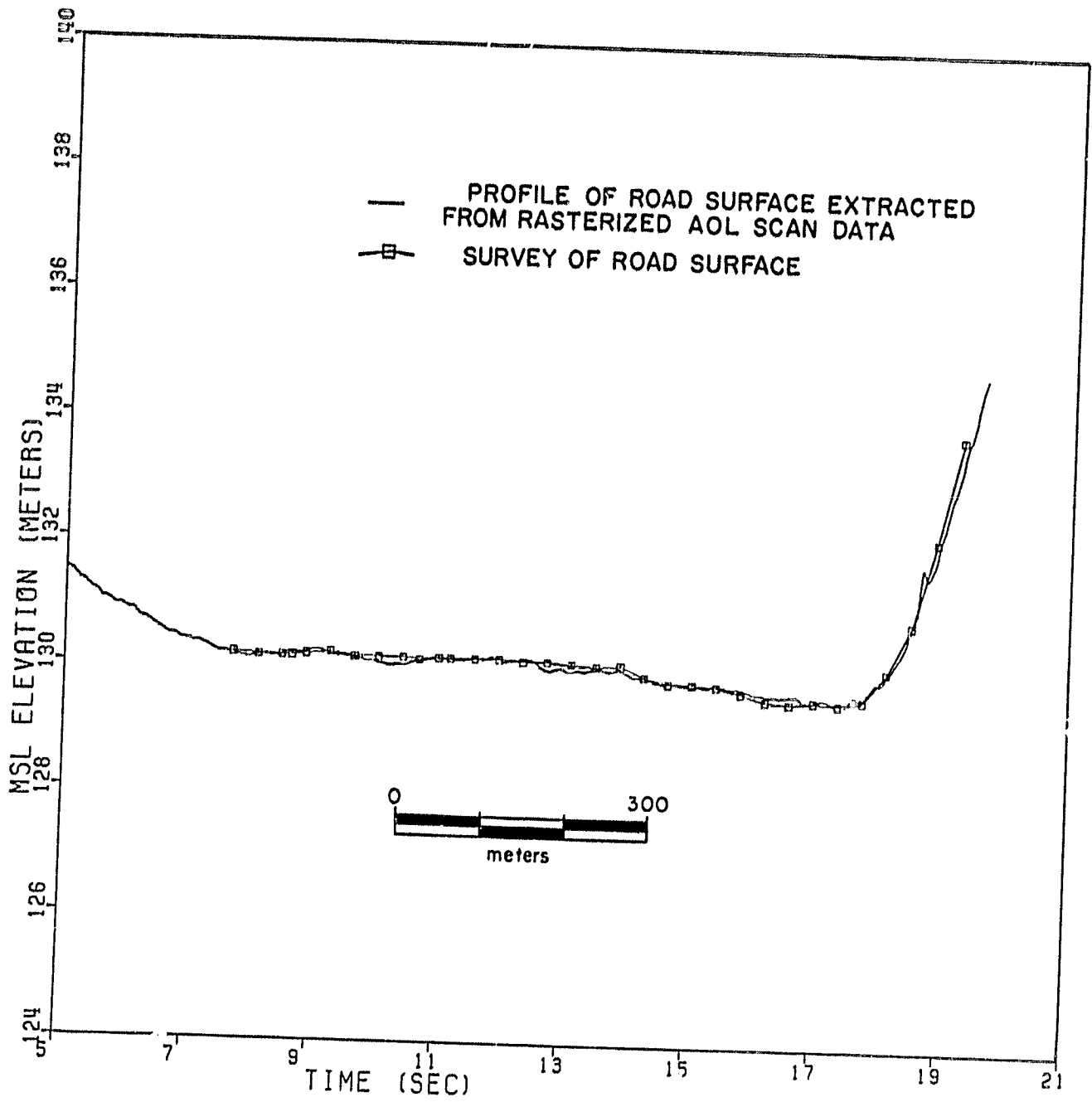
Figure 17.   Comparison of AOL scanning data with ground truth.

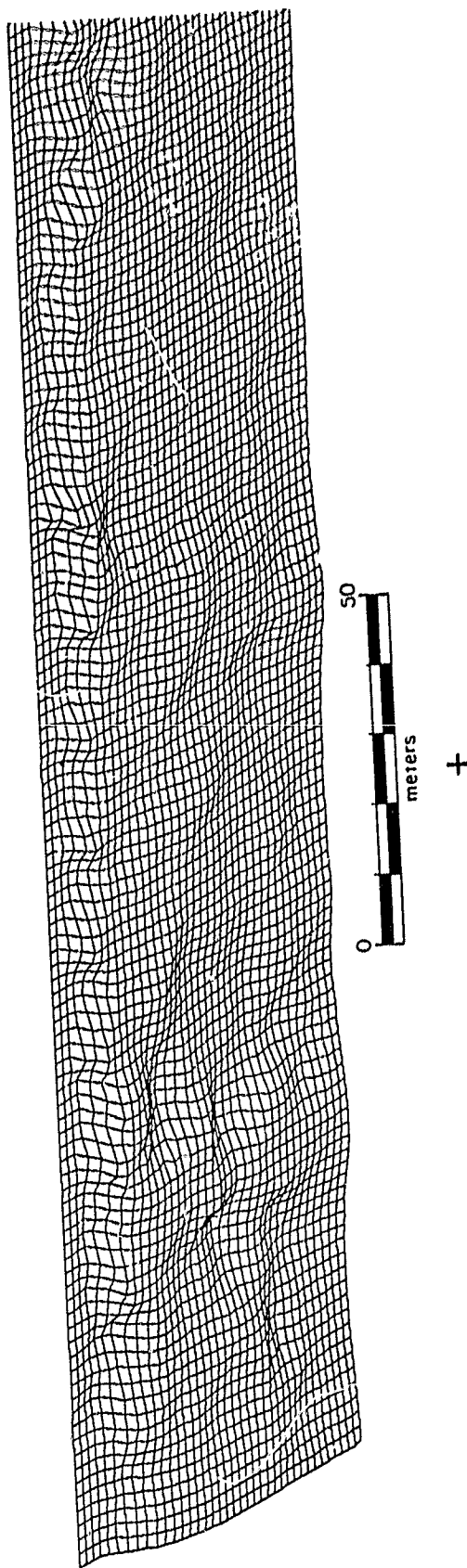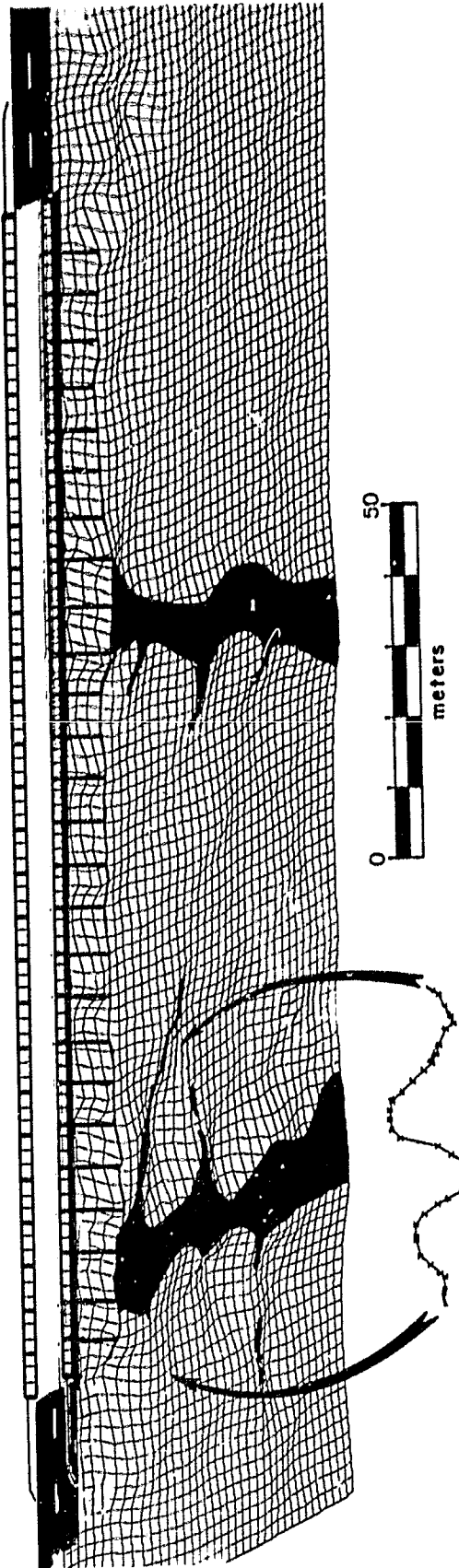Leafing on deciduous trees is expected to adversely effect the capability of a lidar system to penetrate forests due to blocking of the laser beam at both the upper and lower canopy levels; in fact, the growth of annuals may even degrade the resolution of the ground significantly in agricultural areas. Since mid-latitude broad-leafed foliage exists over a 7 to 9 month period of the year (depending on dominant variety and location), this represents a significant "down period" which must be considered in CE decision-making regarding future lidar systems. The degree to which summer foliage conditions affect lidar ground surface mapping is currently not known. Future tests (to be performed in July 1980) will focus on evaluating this important aspect along with extending terrain mapping capabilities to include scanning and the production of detailed contour maps within forested floodplain areas.

CONCLUSIONS

AOL terrain elevation data has been demonstrated to agree with photogrammetry to 12-27 cm (.4-.9 feet) over open ground, and 50 cm (1.6 feet) in forested areas.

An inexpensive ($1,200.00) accelerometer and three ground survey points can effectively be utilized to remove aircraft motion from the data.

The limited analysis of scanning lidar data indicates comparable quality (in 3-D) to profiling data; however, more research and development in the collection and processing of this type of data is needed.

Although a number of methods have been utilized to determine the position of flight lines, navigation/positioning remains a problem for generalized application of an airborne lidar.

APPENDIX A

AIRBORNE OCEANOGRAPHIC LIDAR SYSTEM DESCRIPTION

The Airborne Oceanographic Lidar (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 depth of coastal waters or provide for the detection and resolution of water clarity, oil films, fluorescent dye tracers, and organic pigments including chlorophyll. In performing the above two functions the AOL system must always perform as a high precision laser altimeter, thus allowing the study of surface topography mapping as well. The timing electronics associated with the altimeter portion of the instrument further allows for depth stratification measurements. These vertical dimension measurements coupled with the airborne conical scanning capability of the optical portion of the system, allows wide area three-dimensional maps to be produced. Detailed horizontal resolution is provided by the 400 per second real-time data rate capability.

In the bathymetry mode a nominal 7 nanosecond 2 kW neon laser pulse is transmitted to the water surface where, through Fresnel reflection, a portion of the energy is returned to the airborne optic i receiver while the remainder of the pulse continues through the water column to the bottom and is subsequently reflected back to the receiver. The elapsed time interval between the received surface and bottom pulses allows determination of the water depth. Additional analysis of the amplitude and temporal decay characteristics of all the pulses allows resolution of sea state, surface reflectivity, water transmissivity, as well as bottom reflectivity.

The AOL optical system consists of a rigidly connected three tier optical table arrangement. This is seen in Figure A1. This construction technique affords good structural integrity while maintaining a quasi-laboratory situation for convenient and rapid adjustment, replacement or modification. The upper tier supports the laser transmitter, folding mirrors, beam forming or collimating optics while the intermediate tier carries the 30 cm receiving Cassegrain telescope coupled selectively to the bathymetry phototube detector or fluorosensor. The lowest tier is located beneath the aircraft floor in the cargo bay and supports only the folding flat and nutating mirror conical scanner assembly. A cut-away view of the AOL system as installed on the NASA C-54 aircraft is further provided by Figure A2.

In the bathymetry mode the AOL system laser is filled with neon gas to yield an output wavelength of 540.1 nm. The 400 pulse per second (or less) output is folded into
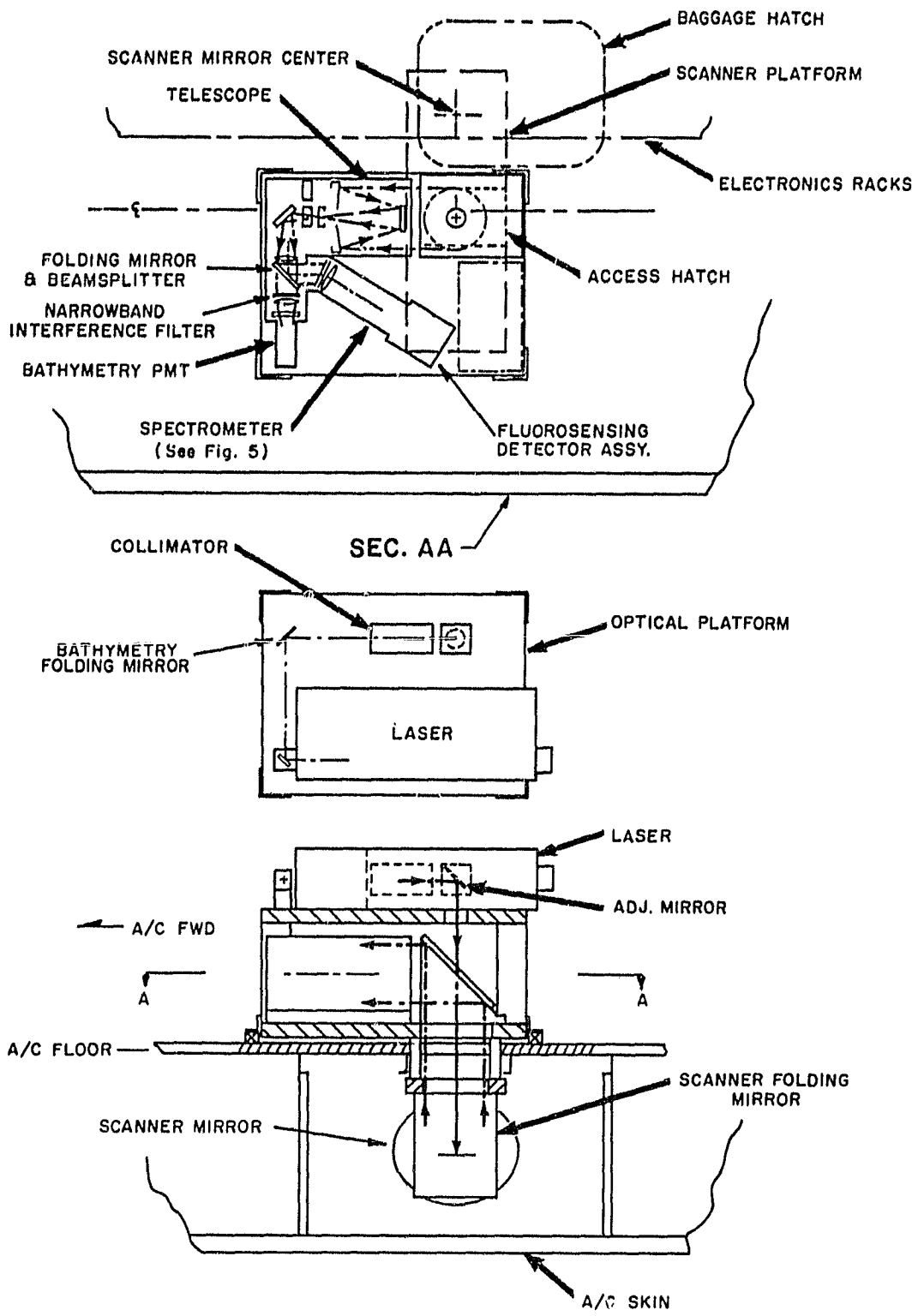
Figure A1. AOL optical table arrangement.
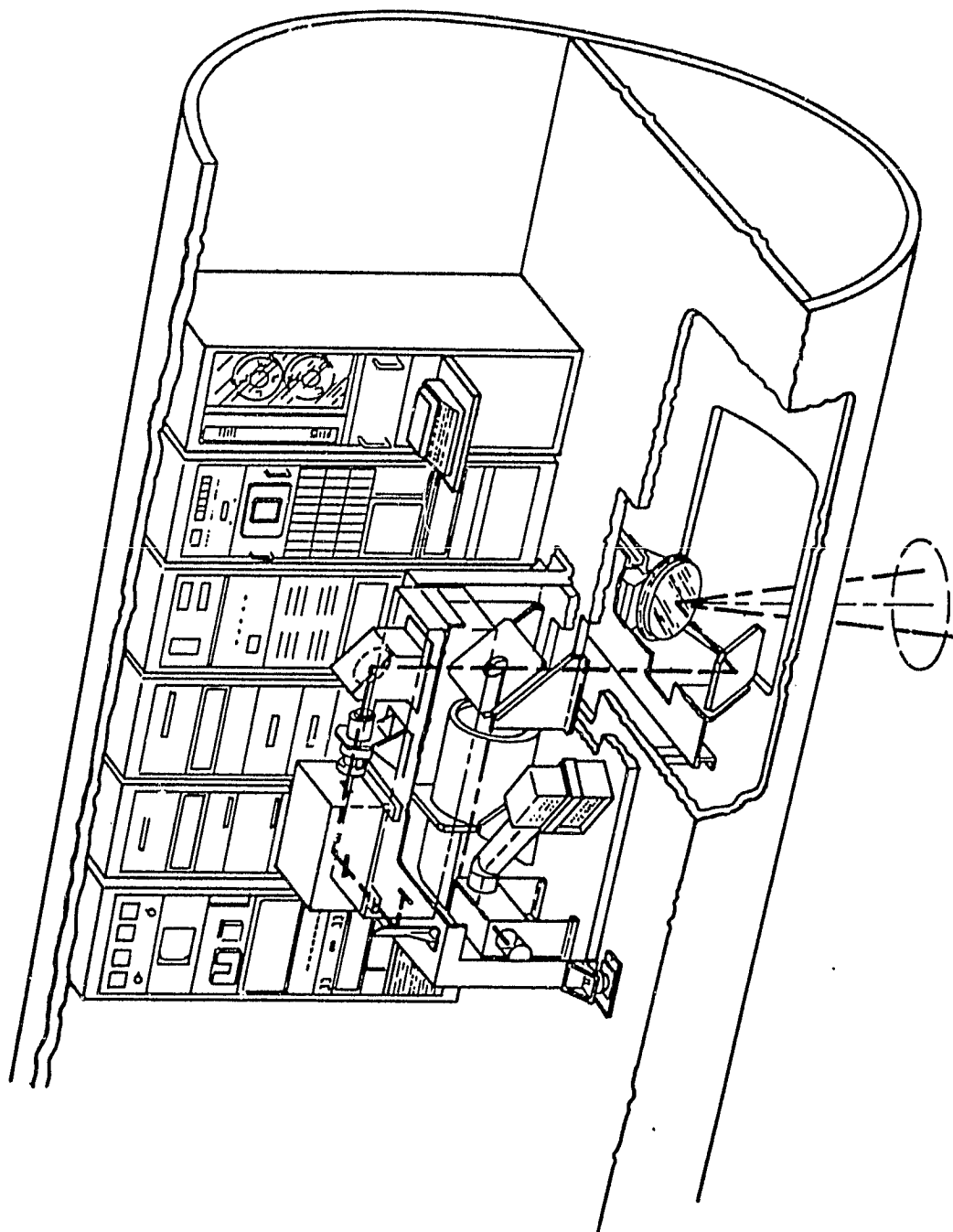
Figure A2. Installation arrangement of the AOL on the NASA C-54 aircraft.

the adjustable beam divergence collimating lens, directed downward through the main receiver folding flat onto the scanner folding flat finally striking the angle-adjustable 56 cm, round, nutating, scanner mirror which directs the beam to the earth's surface. The total ocean surface, volume, and bottom backscattered signals return through the same path but because of their uncollimated spatial extent are principally directed into the 30.5 cm Cassegrain receiving telescope. The horizontal and vertical fields of view of the receiving telescope are each separately controlled by a pair of remotely adjustable focal plane knife edges. The radiation is then collimated and focussed behind the face of the EMI D-279 PMT to avoid weak photocathode areas. The 45° folding flat and beam splitter between the collimating lens and the narrowband interference filter shown in Figure A1 are both used only in the fluorosensing mode.

The PMT analog output waveform is then routed through a multichannel 10X amplifier, fanned-out or reproduced forty times and sent to charge digitizers (CD). The forty charge digitizers are gated "on" sequentially every 2.5 nanoseconds to obtain the proper segments of the waveform. Additionally, the CD's are held "on" for 4.0 nanoseconds. The center of each 4 nanosecond gate remained spaced from its neighbor by 2.5 nanoseconds yielding a 0.75 nanosecond overlap with both adjacent CD's.

APPENDIX B

DATA PROCESSING ALGORITHM DESCRIPTION

This section describes the decision making process for the determination of land sur-
face profiles from Airborne Oceanographic Lidar (AOL) non-scanning data. Aircraft posi-
tioning for this application is determined from a combination of Inertial Navigation
System (INS) velocity, heading, and track angle data, three (minimum) ground survey
points, the AOL range data, and a vertical accelerometer. A straightforward integration
process of the above data, using the ground survey points for control, provides the air-
craft trajectory, relative to the survey, for the 30-60 second duration of a pass. The
aircraft pitch and roll from the INS and the AOL slant range are then used 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, 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 to be recorded by the
AOL electronics. The time difference between the surface and bottom returns yields a
measurement of water depth. An analogous situation exists with 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.

To process the range and waveform data to obtain the above measurements, it is first
necessary to calibrate the waveform data, using an environmental subtraction technique de-
veloped for bathymetry (Swift, 1978). The necessity for the calibration is due to system-
atic errors in the waveform sampling electronics as a function of the energy in the
return, and because of variations in gain and bias for each individual sample gate. The
calibration process amounts to reading a span of data and averaging the values for each
sample gate into a matrix as a function of return signal strength. The referenced bathym-
etry paper utilized data over water which was too deep to produce bottom returns in the
waveform samplers. Unfortunately, the distribution of tree heights does not allow for
such an uncorrelated calibration, and this technique must depend upon having a suffi-
ciently large number of non-bottom returns in each gate to average out the effect of true
bottom signals. (It turns out that this is much less of a problem than the above dis-
cussion might imply, and the technique works quite well.)

The data file is then repositioned at the desired start time, and, as each record is read, the appropriate calibration vector is selected from the matrix by the received signal strength and is subtracted from the raw waveform (see Figure B1). The location (gate or channel number) and magnitude of the peak return in this calibrated waveform is then determined. This information, along with the measured Mean Sea Level (MSL) as determined by the raw slant range and the computed aircraft trajectory, are then passed into a Kalman filter routine. The state model for the Kalman filter is simply a quadratic polynomial as a function of time. Probably an alpha-beta filter would function as well, but the Kalman allows for increased flexibility in filter parameter control (memory, weighting, etc.).

Initialization of the Kalman filter is generally accomplished by starting the data processing over a segment of clear ground, although the capability to start-up in trees exists. The filter reaches steady-state conditions in 4-5 cycles.

A cycle through the filter begins with the prediction of ground level based on prior measurements. A measurement residual is then formed by subtracting this predicted ground level from the input MSL. The residual is then compared to an edit limit (generally 2-3 meters). If within the edit limit, the original measurement is assumed to have been made directly to ground level, with no interfering vegetation, and is processed on through the filter as such. If the residual is outside the edit limit in a negative sense, the ground elevation is assumed to have decreased rapidly or the filter has "lost track," and the filter state is reset to this value. If the residual is greater than the edit criterion, it is then assumed to be a predicted tree height. This predicted tree height is compared to the range of possible tree heights for which the waveform sampler gates could have measured. If the predicted tree height is too tall or too short by more than the edit limit, the measurement is considered to be invalid, and therefore edited from further processing. If the predicted tree height is within bounds, the tree height based on a 5 channel centroid about the peak is then computed. If within .5 m of the predicted tree height and the power in the peak is above a nominal threshold, the combination of range and tree height is assumed to be the ground measurement. The edit limit is once again checked, and processing continues.

If the tree height derived from the largest peak is less than 0.5 m shorter than the predicted, the possibility of a later pulse is examined. (Mid-level branches and low vegetation could produce multiple returns.) A search is made for a later pulse with sufficient amplitude to have been the ground. If found, a comparison is made to determine the resulting tree height closest to the predicted, and that value is chosen for further processing. If a second pulse is not found, the original peak is used, and processing continues.

If the MSL value to be processed in the filter is from a direct slant range measurement to the ground, the sigma is set at 10 cm. If from range and waveform data,

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PHASE OI MISSION O9
PASS 7/2 TERRAIN MAPPING
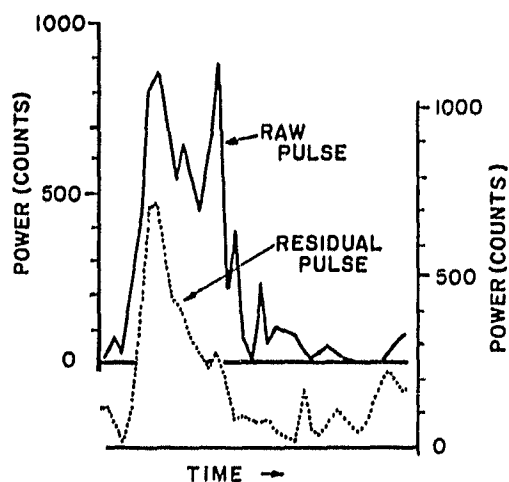
ACTUAL RETURN PULSE FROM TERRAIN MAPPING MISSION
WITH RESIDUAL PULSE SUPERIMPOSED

THE RESIDUAL PULSE WAS DERIVED FROM A SYSTEM AND
ENVIRONMENTAL NOISE SUBTRACTION TECHNIQUE DEVELOPED BY
W.F.C. TO ENHANCE VOLUME BACKSCATTER CHARACTERISTICS
OF RETURN WAVEFORMS.

SWIFT,R.N. AND GOODMAN,L.R., "APPLICATION OF AN ENVIRONMENTAL
SUBTRACTION TECHNIQUE FOR ENHANCEMENT OF AIRBORNE LASER BATHYMETRY"
CONFERENCE OF LASER AND ELECTRO-OPTICAL SYSTEMS, SAN DIEGO, CAL.,
FEBRUARY,1978.

Figure Bl. Example of environmental waveform calibration.

31

30 cm weighting is used. All pertinent data from the above processing is subsequently
written on an output file for plotting, etc. In addition, simple statistics on the
foliage penetration capability are summarized at the end of a program execution (see
Figure B2).

1	112	77	29	8
2	22	43	24	4
3	49	26	14	2
4	10	19	24	0
5	44	21	1	2
6	41	4	7	0
7	46	25	5	0
8	57	22	10	1
9	29	2	3	0
10	38	6	5	0
11	17	4	3	0
12	44	10	3	1
13	25	0	11	0
14	52	4	2	0
15	14	0	0	0
16	29	0	1	0
17	43	2	0	0
18	18	1	0	0
19	4	0	0	0
20	4	0	0	0
21	82	3	4	0
22	34	4	0	0
23	61	8	0	0
24	38	1	0	1
25	8	0	0	0
26	91	6	5	0
27	16	0	0	0
28	0	0	0	0
29	61	28	22	1
30	18	1	0	0
31	19	0	0	9
32	0	0	0	30
33	0	0	0	1
34	0	0	0	1
35	0	0	1	17
36	0	187	84	49

TOTAL NUMBER OF LASER PULSES	3237
NUMBER OF LASER PULSES OVER TREES	2015
NUMBER OF TREE HEIGHTS SENSED FROM WAVEFORMS	1126
NUMBER OF TREE HEIGHTS NOT SENSED FROM WAVEFORMS	504
NUMBER OF TREES TOO SHORT FOR WAVEFORMS	258
NUMBER OF TREES TOO TALL FOR WAVEFORMS	127
PERCENTAGE OF TREE HEIGHTS SENSED	55%

Figure B1. Example of data processing summary.

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15. Supplementary Notes

16. Abstract

Initial results from a series of joint NASA/US Army Corps of Engineers experiments are presented. The NASA Airborne Oceanographic Lidar (AOL) was exercised over various terrain conditions, collecting both profile and scan data from which river basin cross-sections are extracted. Comparison of the laser data with both photogrammetry and ground survey is made, with 12-27 cm agreement observed over open ground. Foliage penetration tests, utilizing the unique time-waveform sampling capability of the AOL, indicates 50 cm agreement with photogrammetry (known to have difficulty in foliage covered terrain).

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