Development of an Airborne Lidar for Characterizing Particle Distribution in the Atmosphere

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Prepared by
SRI International
Menlo Park, California

ELECTRIC POWER RESEARCH INSTITUTE

Development of an Airborne Lidar for Characterizing Particle Distribution in the Atmosphere

EA-1538
Research Project 1308-2

Final Report, September 1980
Work Completed, January 1980

Prepared by

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ABSTRACT

A two-wavelength (0.53 and 1.06 μm) airborne lidar system was constructed and field tested. The ALPHA-1 (Airborne Lidar Plume and Haze Analyzer) was designed to observe smoke plume and atmospheric boundary layer particles over large areas. A data-processing system was designed for both real-time facsimile (gray-scale) display and magnetic tape recording. Multiple microcomputers were used to optimize processing capabilities within the power, weight, and size constraints of medium-sized twin-engine aircraft.

A one-week field program was conducted to evaluate ALPHA-1 performance and reliability. The system successfully observed boundary layer structure over the Los Angeles area and the downwind structure of particulate plumes from the Navajo (Page, Arizona) and Four Corners (Farmington, New Mexico) power plants. Except for one system failure, ALPHA-1 performed very well on its first data-collection mission. The data show the importance of terrain features in establishing particle distributions over urban areas and downwind of large power plants.

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

This project, RP1308-2, involved three specific tasks:

1. Prepare an engineering design for an aircraft-mounted Lidar unit--a unit capable of characterizing particle distribution in the atmosphere

2. Construct and install the unit, along with needed computer and recording devices

3. Field test the Lidar unit

The project was carried out over approximately 18 months, the first three being devoted to the design phase. Field testing was completed in December 1979. This project was not so much one of research, but more one of engineering, i.e., developing a design which incorporated a mix of existing components. No development of new components was needed. In fact, a workable truck-mounted Lidar unit had already been developed. What was needed was a redesigning of the truck systems into one which could be carried by an airplane.

This final report principally covers the results of the field experiments. It does not cover the detailed engineering specifications of the system; however, it does include block diagrams and a list of components for the Lidar system.

PROJECT OBJECTIVE

The goal of this project was to construct a workable Lidar unit which could operate from an airplane. The unit was to use a dual-wavelength laser for gathering information about the size and distribution of particles in the atmosphere. Present methods for studying particle distribution in the atmosphere typically involve the use of aircraft for physically collecting particles for later study. Such techniques produce data from only the one dimension of the flight path. Truck-mounted Lidar systems are an improvement in that they can map a two-dimensional "slice" of the atmosphere, but trucks are limited by the location of roads. Use of an aircraft-mounted Lidar is an obvious solution. In a few hours, an airborne unit can cover a tremendous area while constantly gathering data, in real time (instantaneous readings), along vertical "slices" of the atmosphere from flight altitude down to the ground. Such particle data are of value in: (1) mapping differences in particle distribution over distances of hundreds of miles, (2) mapping plumes at distances well beyond those that are visible to the eye, and (3) mapping the non-uniformity of plumes and mixing zones over thousands of square miles.

PROJECT RESULTS

The Lidar unit was constructed and mounted in a twin-engine airplane. It was field tested in December 1979 in the Los Angeles area, in New Mexico, and in Arizona. Operating at wavelengths of both 1.06 μm and 0.53 μm, boundary layer structure was mapped successfully in the area around Los Angeles, California. In Arizona, cross sections of the plume from the Navajo plant were mapped at distances ranging from 0 to 56 km downwind from the plant--well beyond the point at which the plume was visible to the eye. In New Mexico, the plume from the Four Corners plant was mapped up to 100 km from the stack. In addition, boundary layer structure was mapped at the New Mexico site. The plume studies particularly show the effect of meteorology and terrain on downwind plume transport and diffusion. The EPRI Lidar system has the capability of recording, in real time, data on magnetic tape as well as depicting the data pictorially, in real time, on a facsimile recorder. (Since the completion of this project, the airborne Lidar system has been used successfully and routinely in EPRI's Plume Model Validation study, RP1616.

Ralph M. Perhac, Project Manager
Energy Analysis and Environment Division

ACKNOWLEDGMENTS

Many individuals contributed to the development of ALPHA-1 at SRI. The authors particularly wish to thank Bill Evans and Earl Scribner for their help in the initial design of the system. Jan van der Laan designed and tested the detector circuits. Larry Brieger constructed much of the ALPHA-1 hardware and Bill Dyer constructed the electronic modules.

William Hovelman provided excellent piloting of the SRI Queen Air aircraft. Joyce Kealoha aided with the data presentations included within this report. Finally, Warren Johnson provided many helpful discussions on application of ALPHA-1.

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SUMMARY

SRI International has designed, constructed, and tested for EPRI an airborne lidar system. The ALPHA-1 (Airborne Lidar Plume and Haze Analyzer) was designed to observe remotely smoke plume and boundary layer particles over large regional areas. Two wavelengths--1.06 and 0.53 μm--are used; the near-infrared wavelength (1.06 μm) is emphasized because of larger aerosol-to-molecular scattering ratio and smaller background light levels in the infrared wavelength region than at 0.53 μm. The 1.06-μm wavelength is most suitable for boundary layer particle observations and plume tracking operations; the 0.53-μm wavelength supplements the 1.06-μm data with information on particle size characteristics and closely relates to eye-response (visibility) quantities.

The ALPHA-1 data system uses a microprocessor to format information from the lidar, aircraft location sensors, and other supplementary sensors and writes data records on a nine-track magnetic tape. A second microprocessor formats and writes data on a hard-copy gray-scale (facsimile) recorder in real time. Lidar configuration and specifications are given in the report.

A data-collection program was conducted to evaluate ALPHA-1 capabilities and reliability under actual field conditions expected during boundary layer and plume studies. The ALPHA-1 was on location at Los Angeles for about one day (16 December 1979) to observe boundary layer particle and at Navajo Power Plant for about two days and Four Corners Power Plant for about one day to observe downwind plume structure. Facsimile gray-scale data examples derived from both the magnetic tape records and the real-time data plots are presented. The data show time and space variability of the Los Angeles boundary layer aerosol structure that can be interpreted in terms of atmospheric dynamic processes. The plume cross sections show importance of meteorological structure and terrain features in determining downwind plume transport and diffusion. One example illustrates the use of ALPHA-1 in regional visibility studies. Basically, ALPHA-1 performed very well during this first field program.

Recommendations for modifications and additions are made for improving ALPHA-1 capabilities. Other recommendations are made for developing data analysis programs for quantitatively determining boundary layer particles and plume parameters, evaluating system capabilities for remote measurement of particle size and absolute aerosol density, and for developing the visibility mapping capability of ALPHA-1.

Section 1

INTRODUCTION

This report summarizes work accomplished for EPRI by SRI International under Contract No. RP 1308-2. The objective of this project was to construct and evaluate an airborne lidar capable of characterizing particle distribution in the lower atmosphere. The preliminary design of the system was previously presented in the final report issued under Contract No. RP 1308-1 entitled "Design for Airborne Lidar System."

The present version of ALPHA-1 (Airborne Lidar Plume and Haze Analyzer) is subject to modifications and additions that have been proposed to EPRI. Accordingly, this report does not present a detailed design of the system but rather summarizes system configuration and capabilities and illustrates its performance with data examples. Recommendations to improve the system for use in environmental field studies and to realize the full potential of collected data are discussed.

Section 2

SYSTEM DESIGN

The ALPHA-1 system was designed to observe smoke plume and boundary layer conditions over large regional areas. Two wavelengths--1.06 and 0.53 μm--are used; the near-infrared wavelength (1.06 μm) is emphasized because of larger particle-to-molecular scattering ratio and smaller background light levels in the infrared wavelength region rather than at 0.53 μm. The 1.06-μm wavelengths is most suitable for boundary layer particle observations and plume tracking operations; the 0.53-μm wavelength supplements the 1.06-μm data with information on particle size characteristics and closely relates to eye-response (visibility) quantities. For optimum eye safety, SRI constructed the system using large receiver optics and developed solid-state detector circuits with greater sensitivity than used on previous surface-based lidar systems.

Because lidar systems have extremely high data rates, performance of the system is directly related to the speed of the data-processing system and its peripherals. Although a large minicomputer would have been nearly ideal in terms of processing power, its use was ruled out by the power, weight, and size constraints of a medium-size twin-engine aircraft. Accordingly, one design goal was to make use of multiple microprocessors to achieve power equivalent to a minicomputer. Two high-speed digital converters (10-ns sample intervals) simultaneously sample the two-wavelength backscatter signatures, a 16-bit microprocessor (LSI-11/2) formats and writes data on a nine-track magnetic tape, and a second microprocessor formats and writes data on a hard-copy gray-scale (facsimile) recorder.

Figure 2-1 shows a block diagram of the ALPHA-1 system; system characteristics are presented in Table 2-1. Although the block diagram shows aircraft location information and data from other supplementary sensors being input to the ALPHA-1 data system, we have postponed interfacing existing aircraft sensors because a new aircraft positioning method will be used for future field studies. Table 2-2 lists components purchased for the ALPHA-1 system.

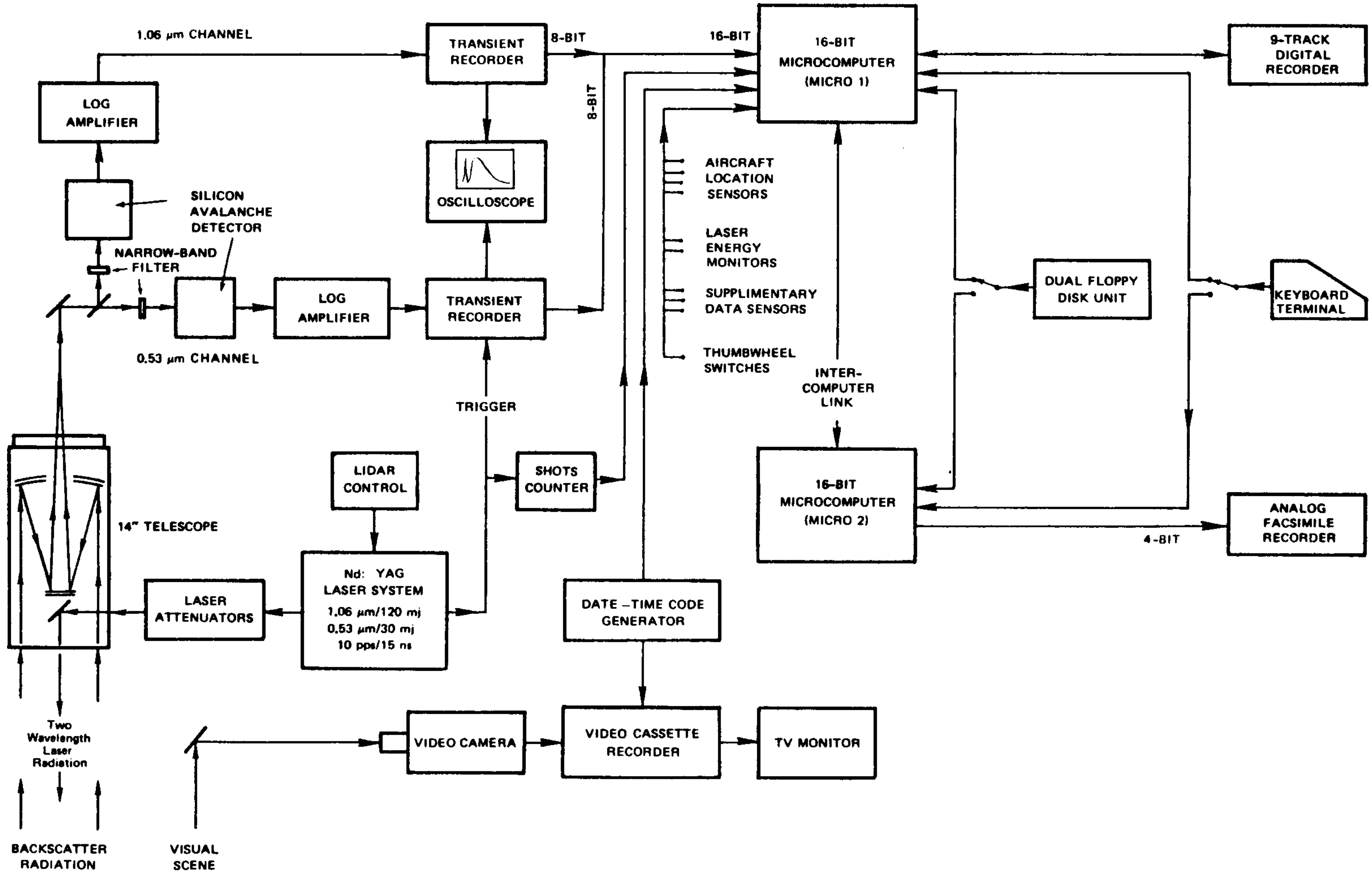


Figure 2-1. Block Diagram of ALPHA-1

Table 2-1

ALPHA-1 SYSTEM SPECIFICATIONS

Transmitter	
Wavelength	Simultaneous 1.06 μm (infrared) and 0.53 μm (green)
Pulse Energy	120 mJ at 1.06 μm 30 mJ at 0.53 μm (Adjustable from 0 to 30 mJ)
Pulse Length	15-17 ns at 50 percent Peak Amplitude
Pulse Repetition Frequency	10 pps maximum
Beam Divergence	2 mrad
Laser Attenuation	0, 5 dB at 1.06 μm 0, 5, 10, 20 dB at 0.53 μm
Receiver	
Telescope	14-inch Schmitt-Cassegrainian
Field of View	Adjustable 1 to 5 mrad
Optical Filtering	Dichroic filter/Long wave pass Narrowband filters: 1.06 μm: 45% max. transmission, 4.6 nm wide 0.53 μm: 45% max. transmission, 0.86 nm wide
Detectors	Silicon Avalanche
Logarithmic Amplification	80 dB dynamic range, 40 MHz
Data System	
Backscatter Digitization	Simultaneous two-wavelength sampling Sample interval: 0.01 μs minimum Resolution: 8 bits
Processing	Dual microcomputers (LSI-11/2)
Program Storage	Dual floppy disk unit
Recording	9-track magnetic tape 4-bit analog facsimile hard copy
Display	Real-time two-channel A-scope Real-time 16 gray-scale analog facsimile
Visual Scene	Recording: video cassette Display: 9-inch TV monitor
Data	Two-wavelength lidar backscatter signatures Aircraft location Data and time Laser energy Real-time program control switch readings 16-channel 10-bit low-speed A/D inputs (supplementary data sensors) Pyranometers (upward and downward looking) Nephelometer Turbulence

Table 2-2

ALPHA-1 SYSTEM COMPONENTS

Item	Manufacturer	Model Number	Acquisition Cost
Laser system	International Laser Systems	Nt-252	$ 46,715
Laser attenuators	CVI Laser Corp.	--	516
Telescope	Celestron International	Celestron 14	6,360
Narrow-band filters (4)	Daystar Filter Corp.	--	3,310
Silicon avalanche detector (3)	General Electric	50 EHS	1,385
Logarithmic amplifier (2)	MVP Electronics	DCL-80AT-40-SI	3,922
Transient recorder (2)	Gould, Inc. Biomation Division	8100	24,843
Video camera	Sony	AVC-3450	677
Video cassette recorder	Sony	SLO-340	1,450
TV monitor	Electrohome	ESM914	213
Date-time code generator	RCA	TC-1440B	1,130
Microcomputer systems (2)	Digital Equipment Corp.	LSI-11/2	11,474
9-track digital tape recorder	Kennedy Co. Western Peripherals	9700 TC-150	7,390
Analog facsimile recorder	Raytheon Ocean Systems	SAR097A	7,495
Dual floppy disk unit	Digital Equipment Corporation	RX01	4,300
Keyboard terminal	Texas Instruments	743	1,291
Oscilloscope	Tektronix	465	2,675
Aircraft racks	Bay Aviation	--	2,500
Lidar port	Bay Aviation	--	8,000
Power supplies	Lambda Electronics	LZS-11, ASSY 13955, LGS-6-24-OV-R	3,220
Miscellaneous Hardware, optics, Electronics, metal stock, etc.			16,149
TOTAL ACQUISITION COST			$155,015

Figures 2-2, 2-3, and 2-4 are presented to illustrate the physical layout of the ALPHA-1 system. The seating arrangement was designed to accomodate two persons within the cabin area so that each would have access to viewing the real-time facsimile recorder [shown between the two crew members in Figure 2-4(b)]. This arrangement provides the crew members with the optimum opportunity for maintaining lidar operation while analyzing the real-time data plot for atmospheric structure and communicating this information through a radio link. When needed, a third crew member can direct the sampling aircraft and record operational information from the copilot position.

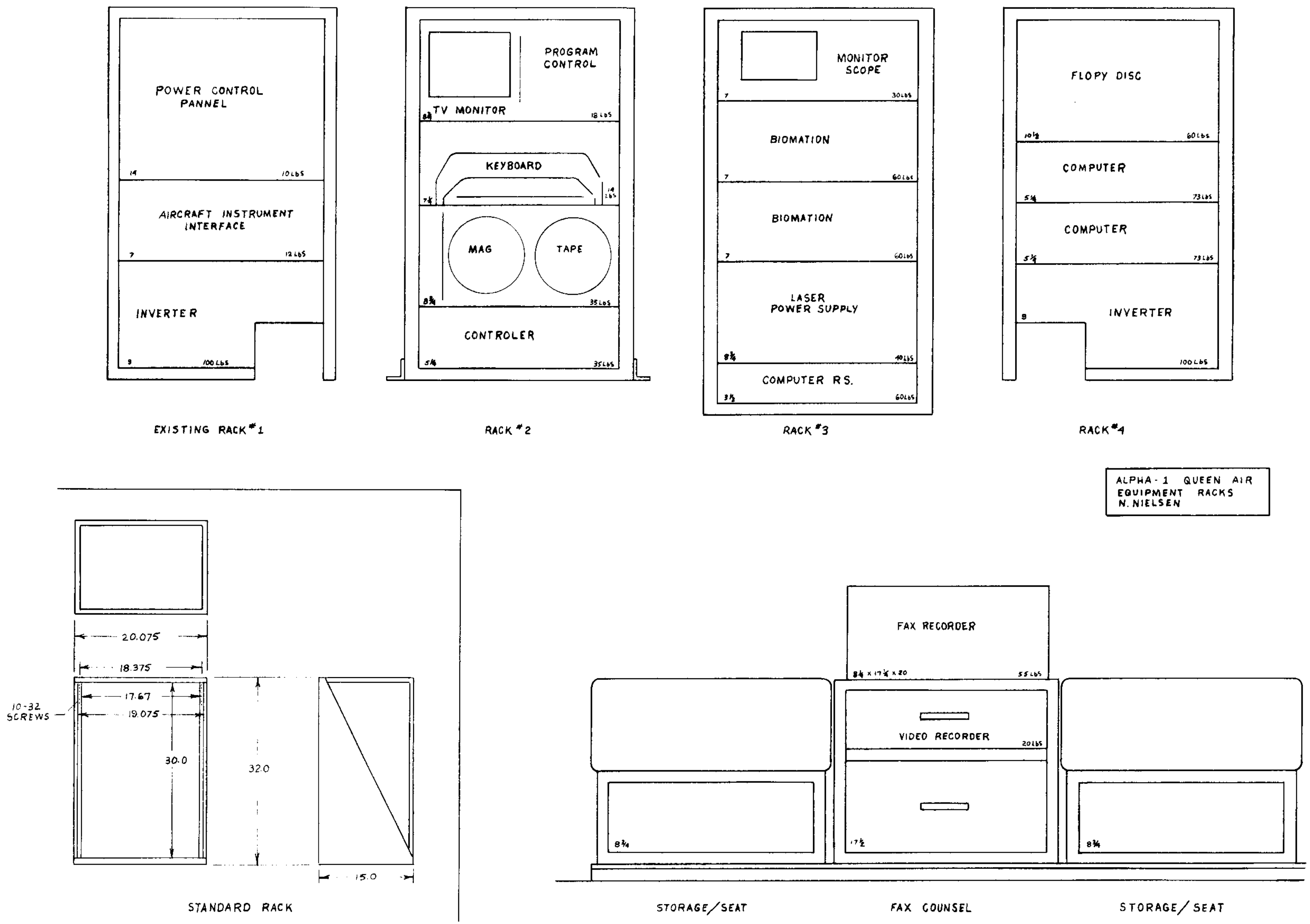


Figure 2-2. Cabin Layout of Queen Air B-80/8800 with ALPHA-1 Installed

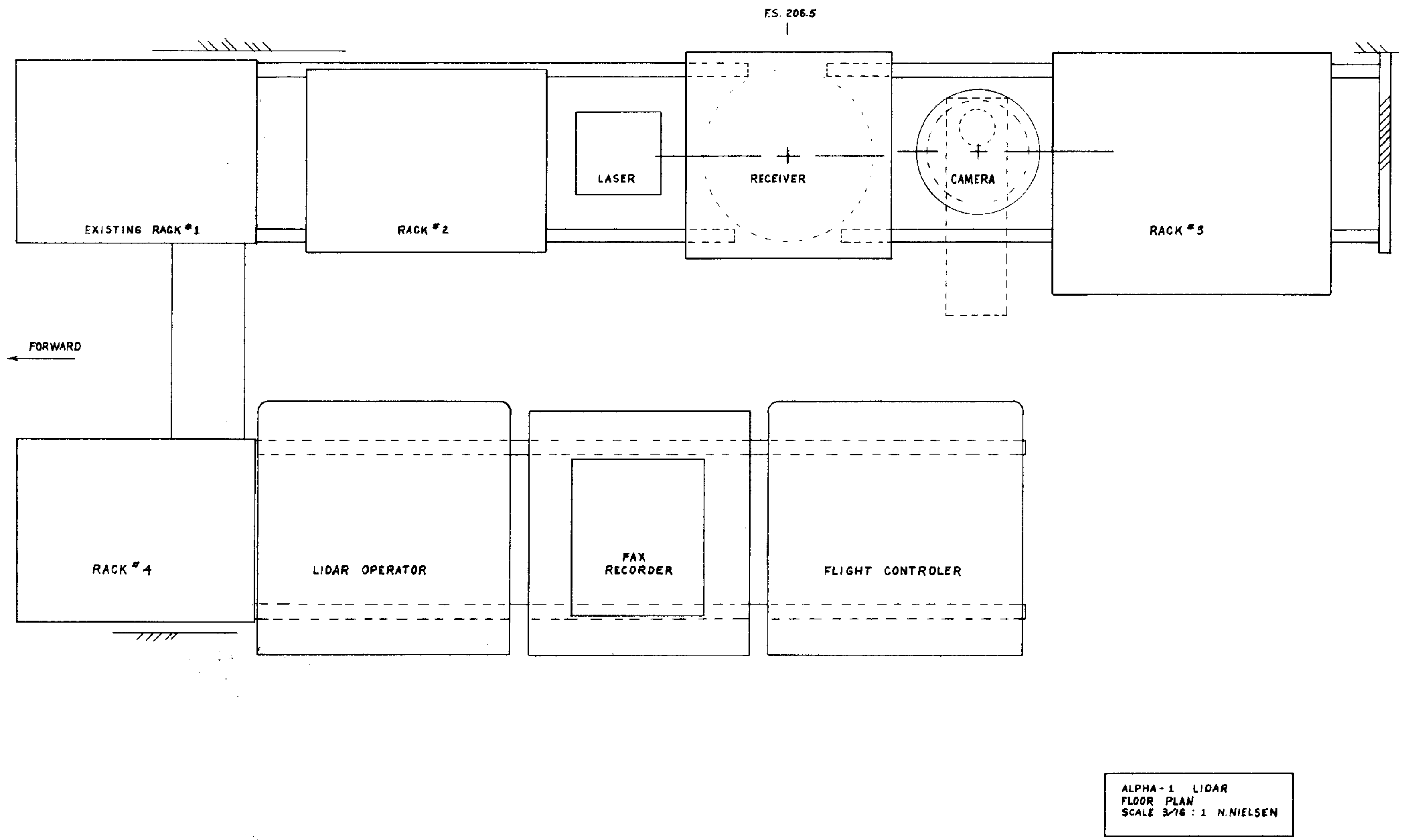


Figure 2-3. ALPHA-1 Rack Layout

Figure 2-4. ALPHA-1 Aircraft

Section 3

SYSTEM CAPABILITIES AND LIMITATIONS

The present ALPHA-1 system capabilities are primarily limited by existing software. The ALPHA-1 system as it currently exists is capable of:

1. Recording both 1.06- and 0.53-μm wavelength backscatter signatures on magnetic tape and plotting the 1.06-μm data on the facsimile recorder in real time. The 0.53-μm data can be plotted in real time by swapping the 1.06- and 0.53-μm inputs to the two Biomation (digitizer) units.

2. Plotting the 1.06- or 0.53-μm data on the facsimile recorder in real time without recording data on magnetic tape.

3. Recording 1.06- and 0.53-μm data on magnetic tape without facsimile recording.

4. Retrieving the 1.06- or 0.53-μm data from magnetic tape and plotting the data on the facsimile recorder. (Simultaneous plotting of both wavelength data has not yet been achieved.)

5. Operation at a laser fire rate of up to 5 laser pulses per second. (More development is required for operation at the maximum laser fire rate of 10 pulses per second.)

The ALPHA-1 system is not now capable of:

1. Recording of aircraft location information.

2. Program control of lidar operating parameters.

3. Operator control of computer processing without program reloading.

4. Complete data recording at a laser fire rate greater than 5 laser pulses per second.

Section 4

SYSTEM PERFORMANCE

In December 1979, the ALPHA-1 system was field tested under conditions expected during boundary layer particle and plume studies. In addition to evaluating system performance, the field program also afforded the opportunity to develop preliminary flight procedures for plume-tracking operations. During this field program, data could not be recorded on both the magnetic tape and facsimile recorder at the same time, i.e., either one recorder or the other was used. (This has since been corrected.)

The design for the field program called for sampling the Los Angeles boundary layer, followed by sampling of plumes downwind of the Mohave, Navajo, and Four Corners power plants. These sites were selected to provide for a variety of sampling conditions, including clean and dirty plumes in both flat and complex terrain. Total flying time was to be limited to about 30 hours.

The ALPHA-1 was on location at Los Angeles for about one day, Navajo for about two days, and Four Corners for about one day (Mohave was not operating). A lidar malfunction required about half a day for repair while at the Four Corners site. The data presented below illustrate the ALPHA-1 capabilities; however, the data are somewhat misleading in that computer failures caused more frequent data gaps than indicated.

LOS ANGELES BOUNDARY LAYER

The ALPHA-1 system was operated over the Los Angeles area (Figure 4-1) to evaluate its capabilities for boundary layer particle observation. Data presented in Figure 4-2 were recorded on magnetic tape and later played back to generate facsimile gray-scale displays. Data collected during the morning hours on 16 December 1979 (taken at the 1.06-μm wavelength) shows a 200-m deep boundary layer. By 1600 hours, PST, the pollution layer has increased in density and depth [Figure 4-2(b)]. Elevated aerosol layers near the San Gabriel Mountains result from transport of the near-surface polluted air up the mountain slopes and an elevated wind reversal. Figure 4-2(c) presents the 0.53-μm wavelength data for the same time period as

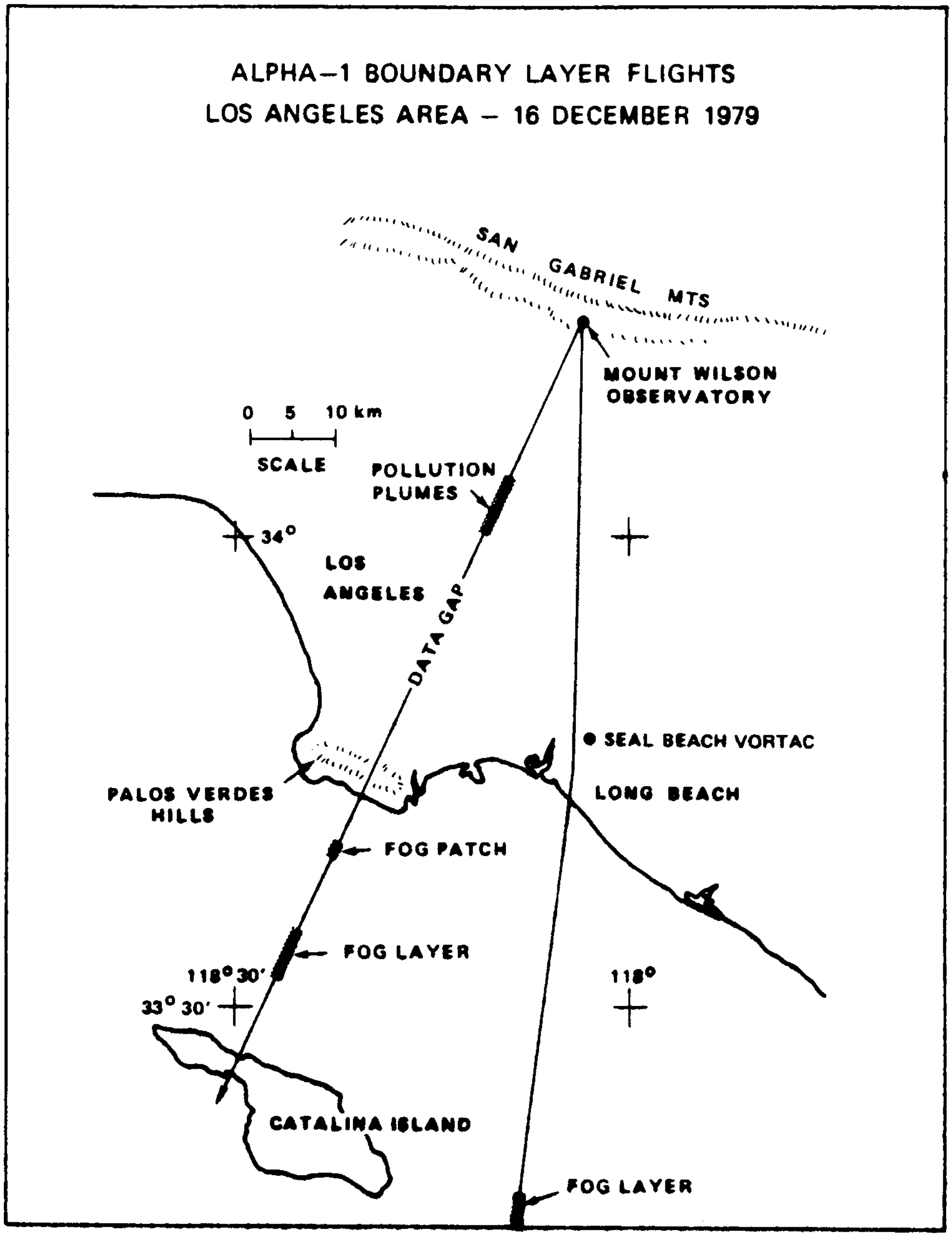
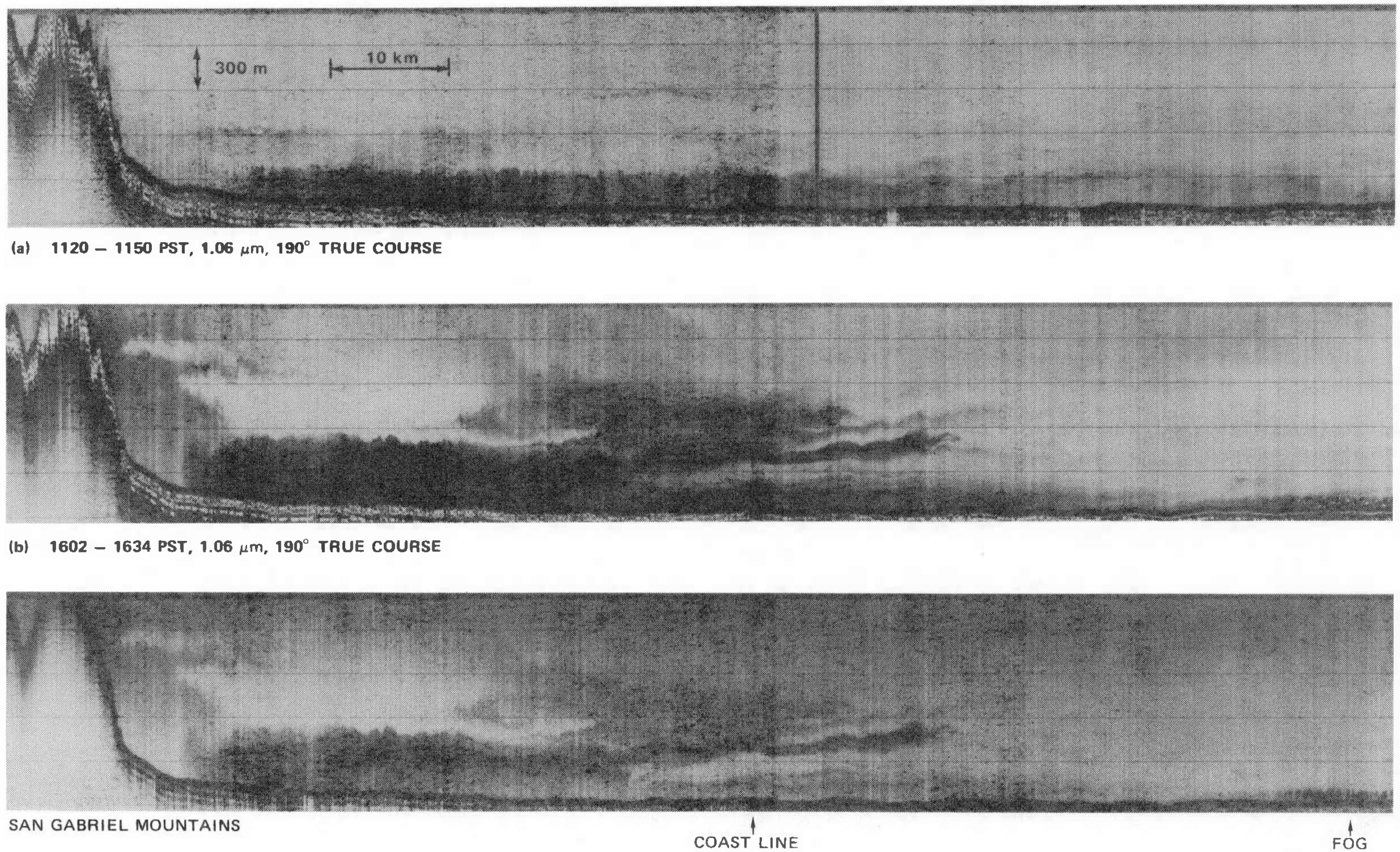


Figure 4-1. Los Angeles Area ALPHA-1 Flight Paths, 16 December 1979



(a) 1120 – 1150 PST, 1.06 μm, 190° TRUE COURSE

(b) 1602 – 1634 PST, 1.06 μm, 190° TRUE COURSE

(c) 1602 – 1634 PST, 0.53 μm, 190° TRUE COURSE

Figure 4-2. Los Angeles boundary layer structure derived from ALPHA-1 magnetic tape records, 16 December 1979.

Figure 4-2(b). At the visible, the ratio of particle-to-molecular scattering is less than at 1.06 μm, resulting in less contrast between dirty and clear air regions. These data illustrate the two-wavelength and tape-recording capability of ALPHA-1. A pulse rate of only 1 pps was used to increase the distance traveled before the magnetic tape storage was exhausted.

Figure 4-3 presents the real-time facsimile records (1.06 μm) collected along the flight path crossing over Catalina Island. A pulse rate of 5 pps was used during all real-time facsimile plotting and explains the difference between horizontal scale factors of Figure 4-2 and 4-3. The flight path for the Figure 4-3 data was chosen so that ALPHA-1 would pass over the most visual pollution source in the Los Angeles area. The dense elevated plumes are shown in the lidar cross section. Biomation 8-bit data are available to plot; however, the facsimile recorder has only 4-bit (16 gray step) capability. Therefore, in order to obtain increased sensitivity of the facsimile record, the middle four bits were plotted. This explains the reversal of gray scales (from black to white) for very dense aerosol plumes. In future ALPHA-1 development efforts, we plan to incorporate real-time program control of plot factors to eliminate gray-scale reversals. The data in Figure 4-3 illustrates the real-time facsimile plotting capabilities of ALPHA-1.

NAVAJO POWER PLANT PLUME

On 17 December, the ALPHA-1 system was flown from Los Angeles to Page, Arizona, site of the coal-burning Navajo Power Plant, which produces about 800 MW per unit of power. The particulate plume is only visible at ranges of less than 1 km from the plant; however, the NO_2 plume is often visible at greater distances under proper viewing conditions.

The plume was flown at cross sections at distances of 0, 0.6, 1.8, and 5.5 km downwind of the plant (Figure 4-4). The data indicate a temperature inversion (stable layer) about 700 m above the plant. A change in wind direction at this height caused a fanning out of the plume top where as the lower plume remained relatively concentrated. Figure 4-5 presents plume cross sections at downwind distances of 9.3, 18.5, and 27.8 km. At a distance of 9.3 km, the plume has become stratified in a W shape and continues to elongate to a downwind distance of 18.5 km. At 27.8 km, the plume came in contact with the terrain and the plume's horizontal extent is less than at shorter downwind distances. We could not locate exactly the plume cross sections because aircraft location information was not

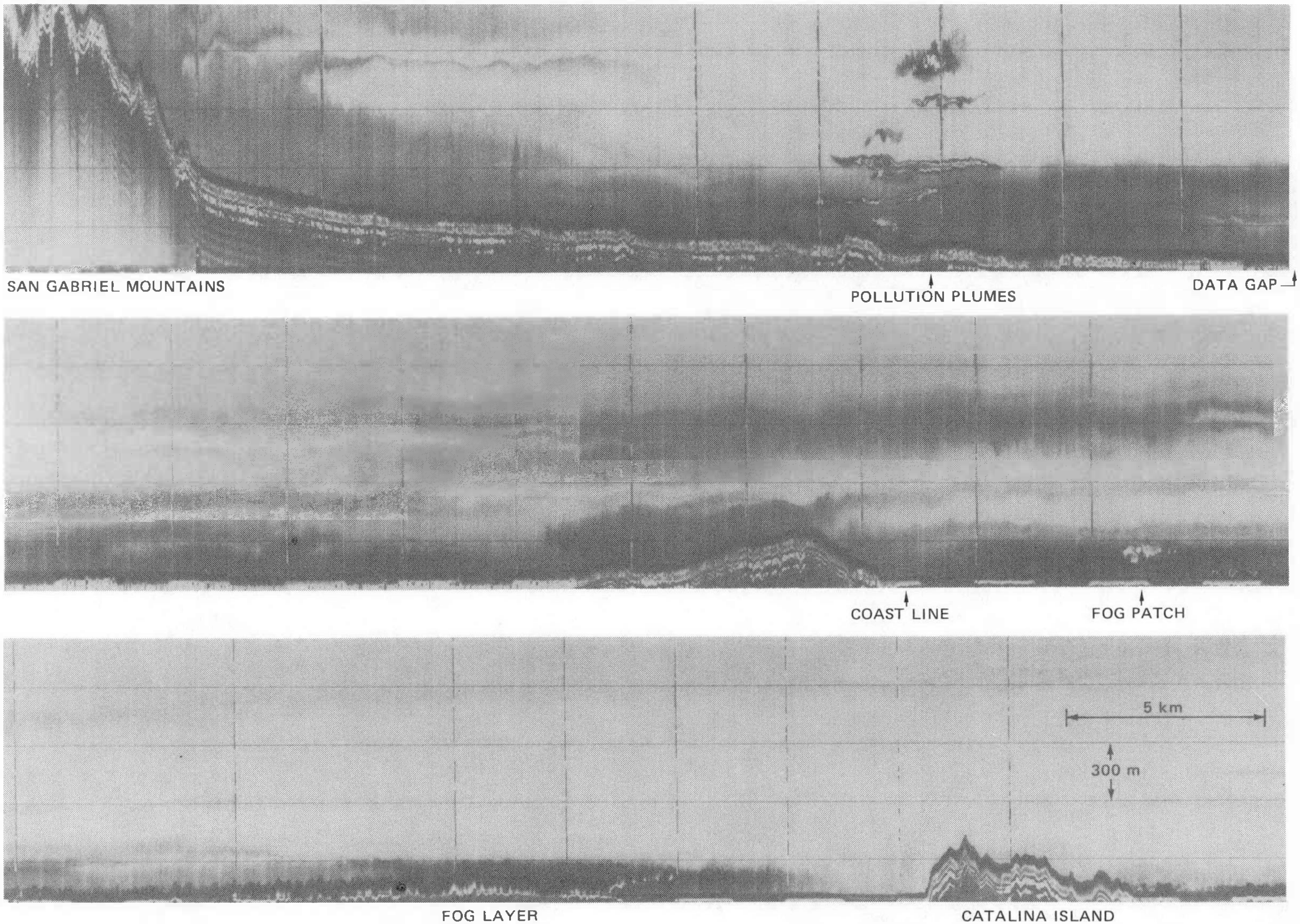
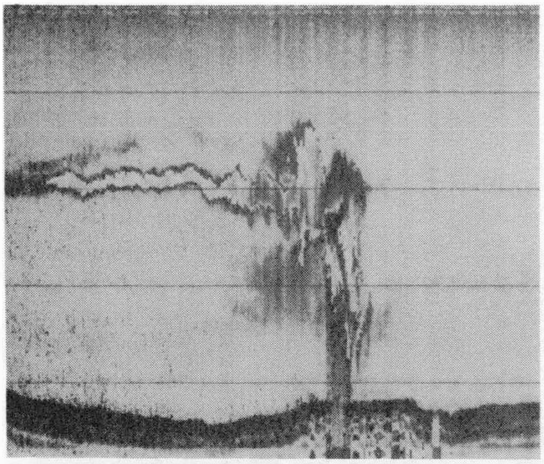
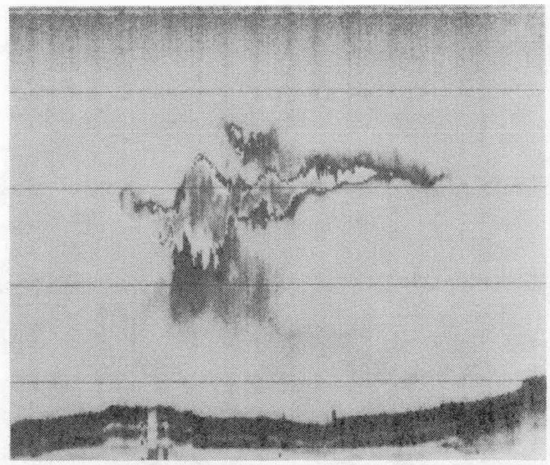


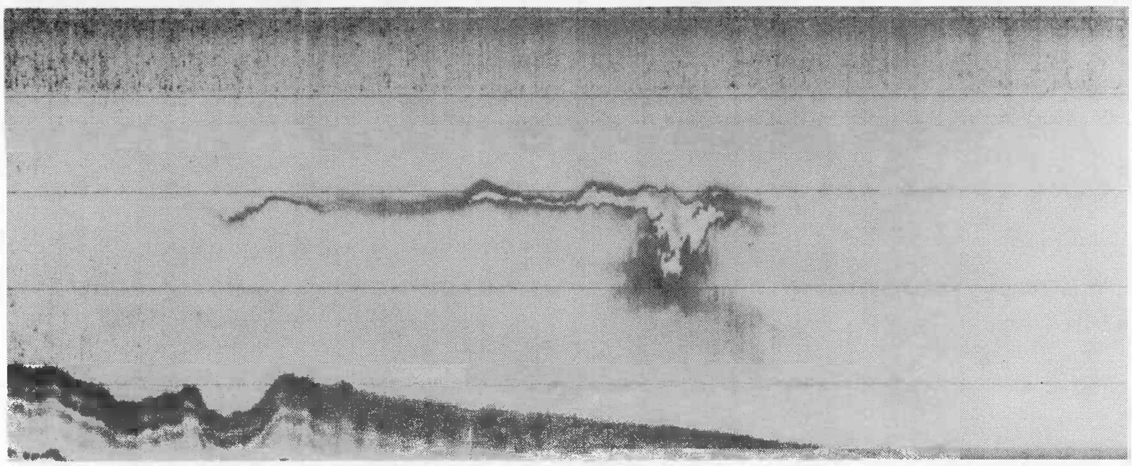
Figure 4-3. Los Angeles boundary layer structure derived from ALPHA-1 real-time facsimile display (1.06 μm), 1700-1730 PST, 16 December 1979.



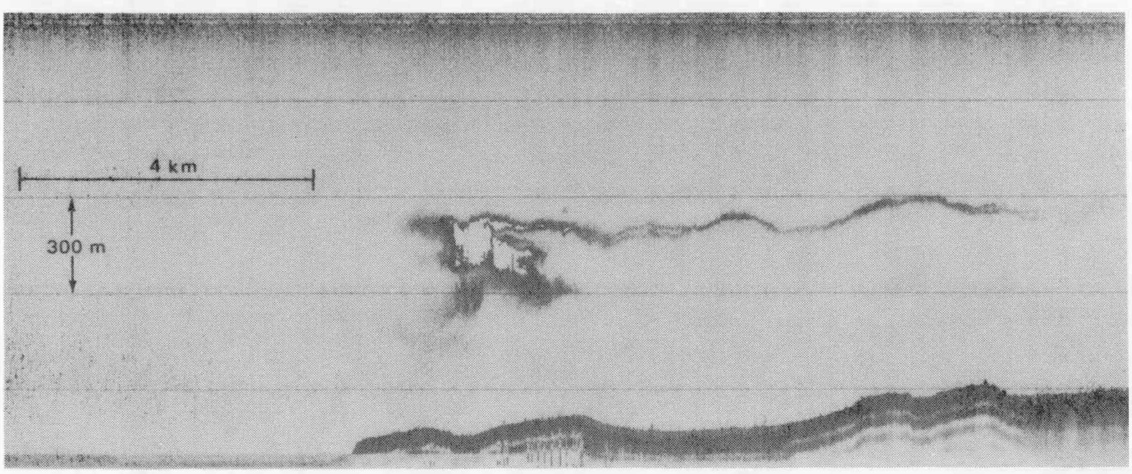
(a) OVER PLANT, 1554 MST, 024° TRUE COURSE



(b) 0.6 km WEST OF PLANT, 1557 MST, 204° TRUE COURSE

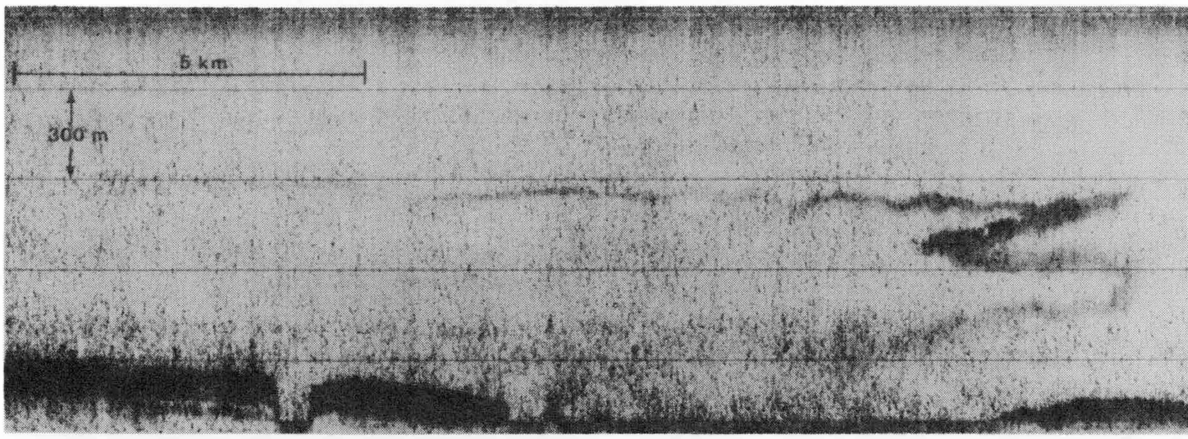


(c) 1.8 km WEST OF PLANT, 1600 MST, 024° TRUE COURSE

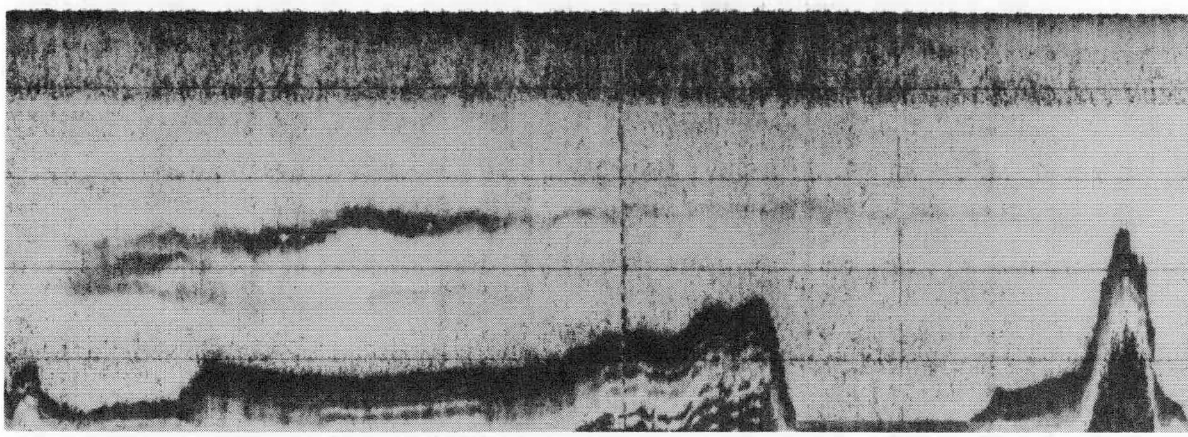


(d) 5.5 km WEST OF PLANT, 1604 MST, 194° TRUE COURSE

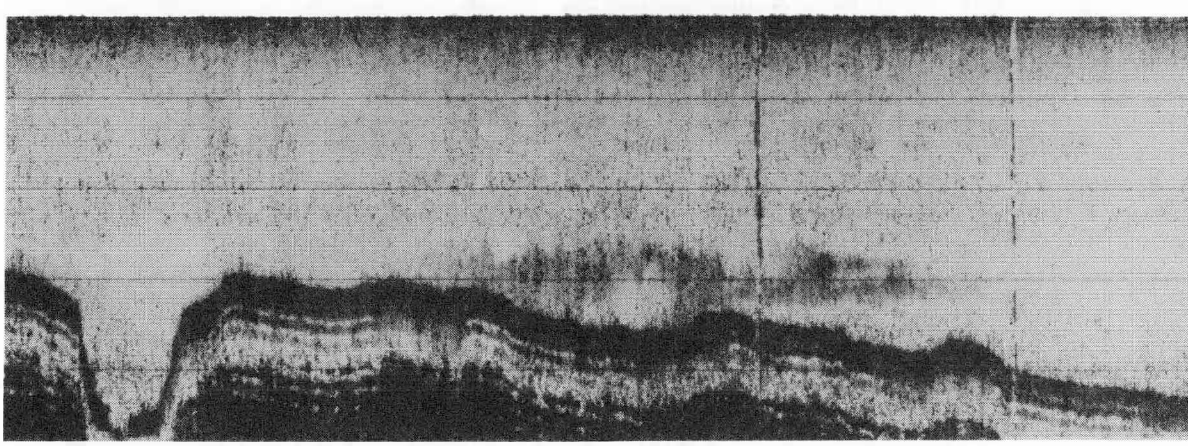
Figure 4-4. ALPHA-1 lidar cross sections of Navajo Power Plant plume 0, 0.6, 1.8, and 5.5 km downwind from plant (1.06 μm), 1600 MST, 17 December 1979.



(a) 9.3 km WEST OF PLANT, 1609 MST, 014° TRUE COURSE



(b) 18.5 km WEST OF PLANT, 1618 MST, 194° TRUE COURSE



(c) 27.8 km WEST OF PLANT, 014° TRUE COURSE

Figure 4-5. ALPHA-1 lidar cross sections of the subvisible Navajo Power Plant plume 9.3, 18.5, and 27.8 km downwind from plant (1.06 µm), 1600 MST, 17 December 1979.

recorded. Future improvements of ALPHA-1 will include automatic recording of location information. For these data, location information was based on visual observation relative to the plant and aircraft heading readings taken from the instrument panel.

Figure 4-6 shows plume cross sections at approximate downwind distances of 37, 46, and 56 km. At these distances, the plume elongated into a single layer that extends only about 100 m above the highest terrain features.

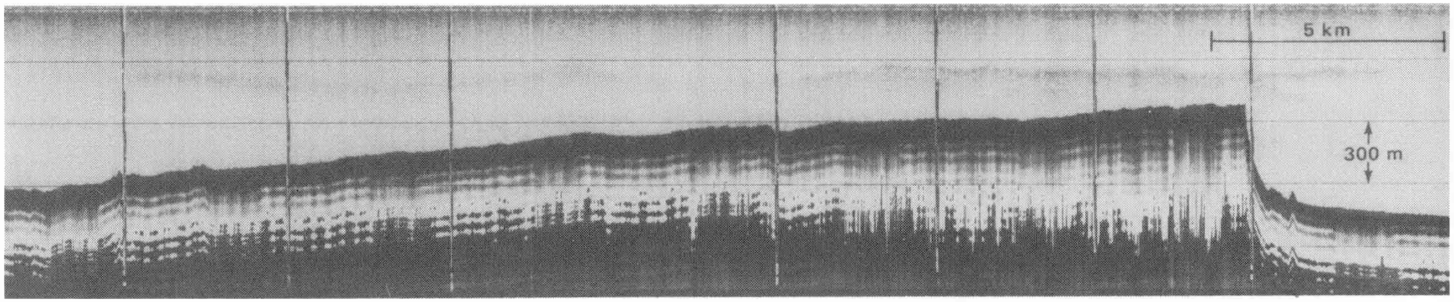
ALPHA-1 was used to make plume cross sections during the morning (0800 MST) of 18 December 1979 (Figure 4-7). As shown by the data (Figure 4-8), the plume remained relatively concentrated to a downwind distance of at least 37 km. The 37-km cross section indicates that the plume was being channeled by the Vermillion Cliffs. The 56-km cross section shows that the plume had elongated, becoming less concentrated and extended over Marble Canyon south of the Vermillion Cliffs. Aircraft flights made near 1400 MST (not presented here) showed the midday plume had become extremely elongated (about 25 km wide and less than 100 m thick) at only 9 km downwind. The plume had a V shape, indicating elevated directional wind shear as was commonly observed using surface-based lidar observations made during the Tennessee (Cumberland Power Plant) Plume Study (Uthe et al., 1979).* We had planned to conduct a diurnal study of the Navajo plume with two additional flight periods later in the day; however, the lidar malfunctioned during the 1900 MST flight and no further data were collected on this day.

The Navajo plume cross sections illustrate the plume tracking capabilities of ALPHA-1 for relatively long downwind distances from a power plant generating a relatively clean particulate plume.

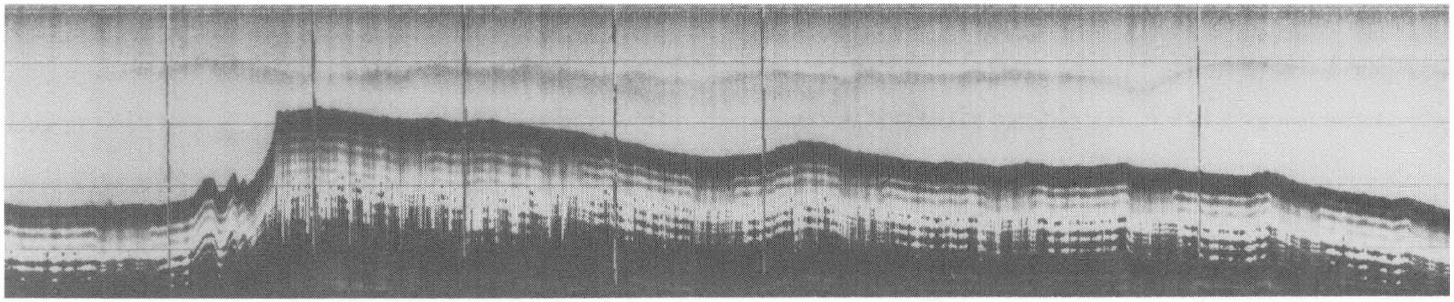
FOUR CORNERS POWER PLANT PLUME

On 19 December, ALPHA-1 was flown to Farmington, New Mexico, site of the Four Corners Power Plant. Because the cause of the lidar malfunction (see above) was not determined during this flight, the lidar sensor had to be removed from the aircraft at Farmington for inspection. The problem was a slight misalignment of the coaxial transmitter optics that probably occurred during an aircraft landing. The optics were aligned and temporarily cemented in place in time to conduct a Four Corners plume study just before sunset.

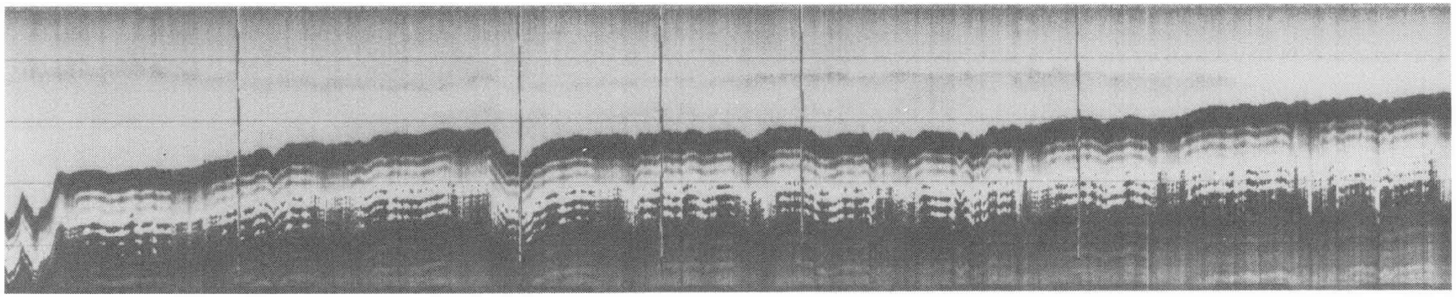
*References are listed at the end of the report.



(a) 37 km WEST OF PLANT, 1639 MST, 194° TRUE COURSE



(b) 46 km WEST OF PLANT, 1646 MST, 014° TRUE COURSE



(c) 56 km WEST OF PLANT, 1700 MST, 194° TRUE COURSE

Figure 4-6. ALPHA-1 lidar cross sections of the subvisible Navajo Power Plant plume 37, 46, and 56 km downwind from plant (1.06 μm), 1600 MST, 17 December 1979.

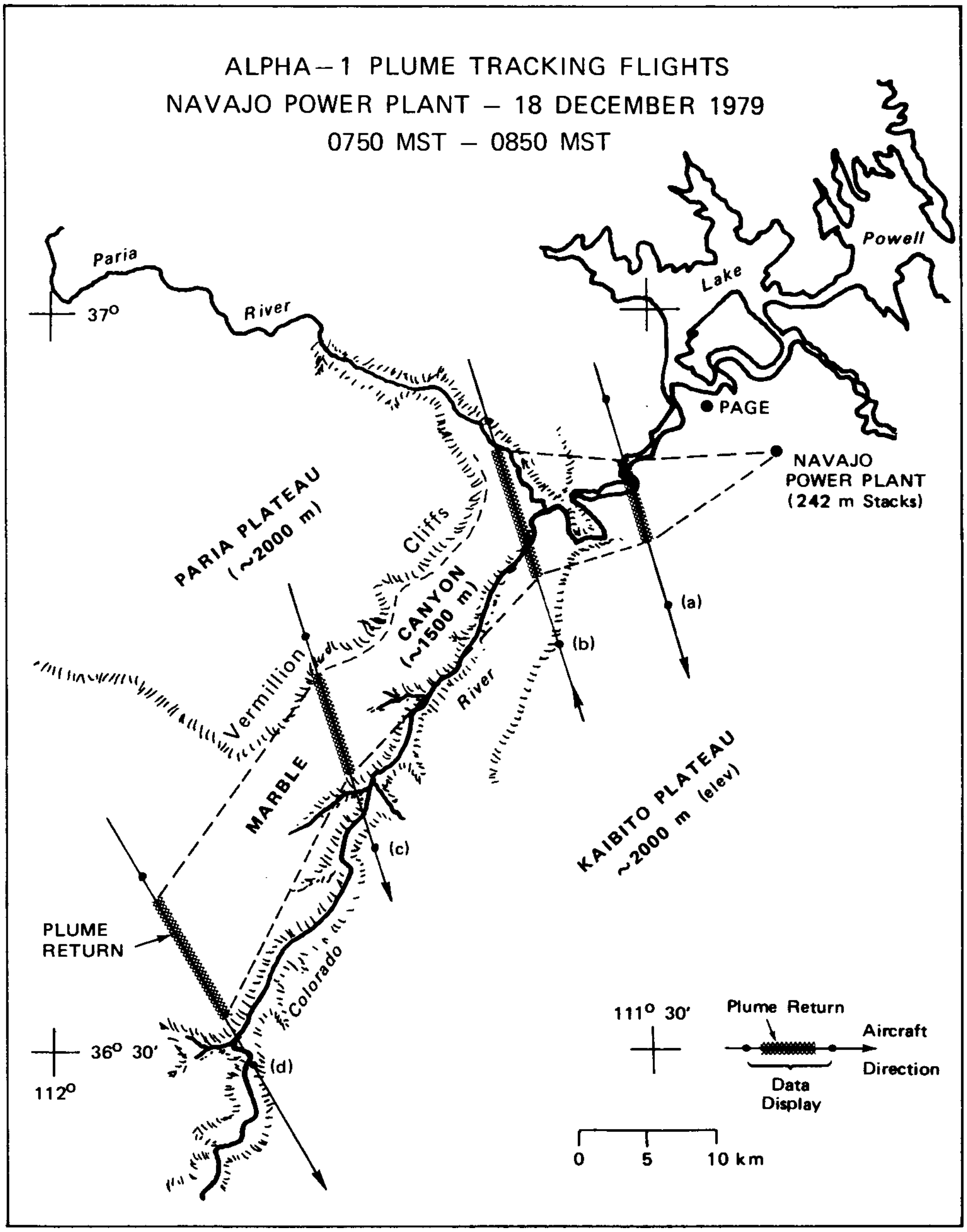


Figure 4-7. Navajo Power Plant area ALPHA-1 flight paths and locations of plume returns, 0800 MST, 18 December 1979.

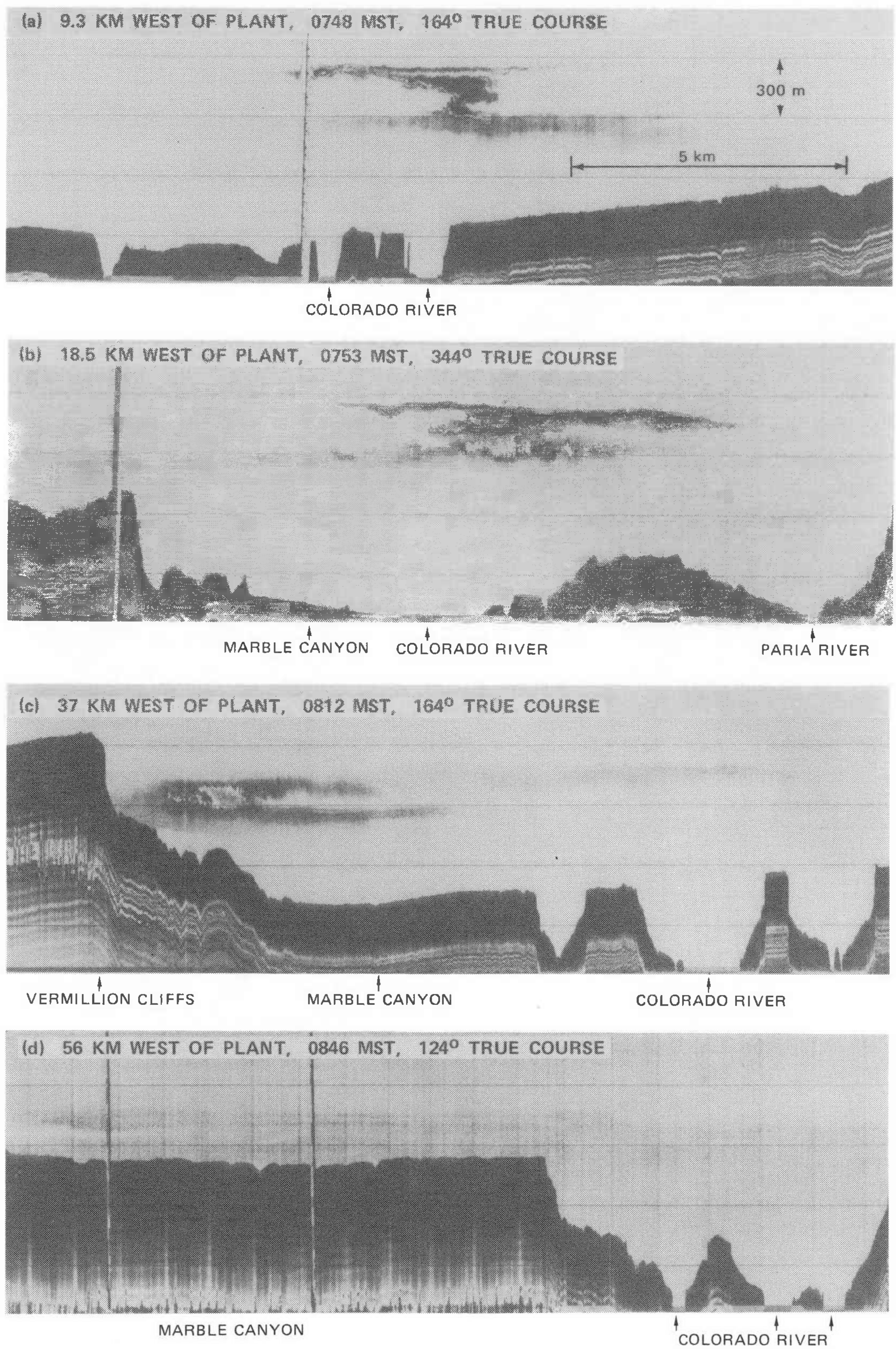


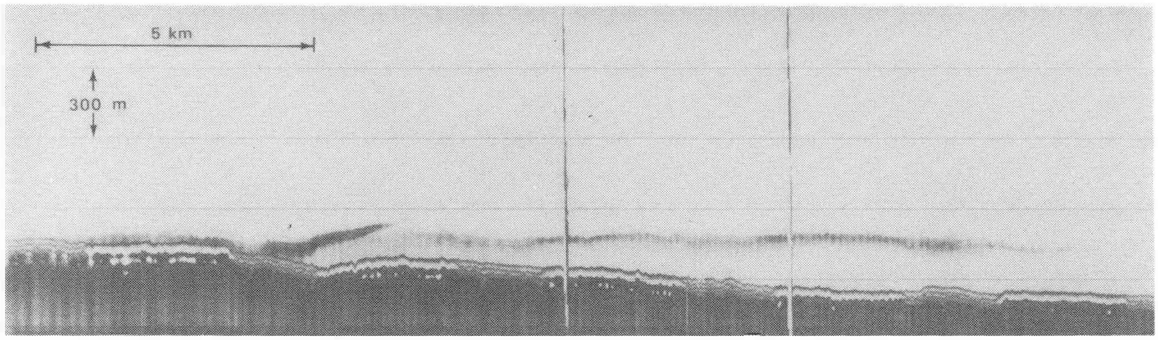
Figure 4-8. ALPHA-1 lidar cross sections of Navajo Power Plant plume 9.3, 18.5, 37, and 56 km downwind from plant (1.06 μm), 0800 MST, 18 December 1979.

Figure 4-9(a) shows a lidar cross section taken from the facsimile recorder at a downwind distance of 18.5 km from the plant. The stratified plume intersects the terrain at the highest elevation point.

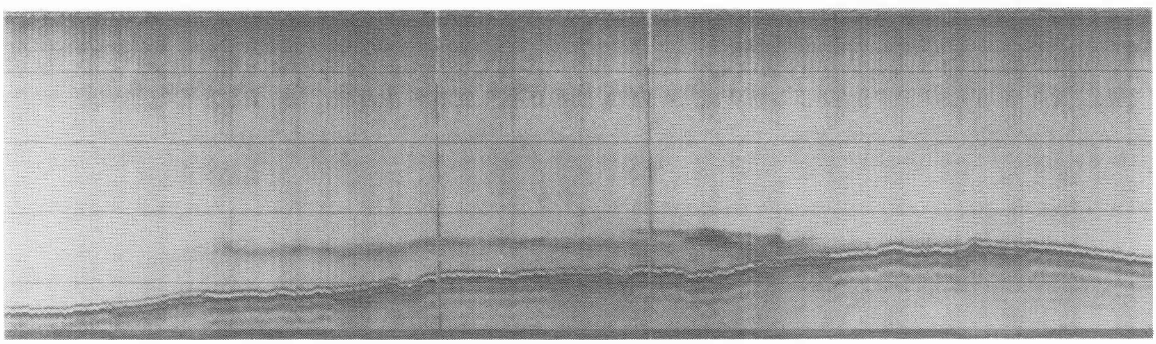
A second pass of the plume at this distance was made with the 0.53-μm wavelength being plotted rather than the 1.06-μm wavelength. Figure 4-9(b) is the facsimile record for the second pass across the plume and this record also shows the plume intersecting the terrain at its highest point. As expected, the ratio of plume-to-background return is less at the 0.53 μm wavelength than at the 1.06 μm wavelength. A more quantitative analysis of the difference in plume returns at the two wavelengths requires calibration of the amplitude response of the lidar system, as discussed further in Section 5 of this report. Figure 4-9(c) is a 1.06-μm wavelength data plot of the plume cross section at a downwind distance of 37 km made during an earlier time (1843 MST). This cross section shows the plume bending downward to intersect the surface.

On the morning of 20 December, an easterly wind allowed us to investigate the downwind structure of the Four Corners plume during the return flight to California (Figure 4-10). The lidar sensitivity (receiver gain) was reduced to keep the plume returns from saturating the facsimile gray-scale display; consequently, the clear-air structure was not observed on these data. As shown in Figure 4-11, a fanning plume tilted upward toward the north was observed with vertical mixing to the surface of the lower plume particulates. This is consistent with earlier lidar observations of the Keystone plume showing that when fumigation occurs during mid-morning hours, it starts at the bottom left edge of the plume looking downwind (Johnson and Uthe, 1971). The plume remains relatively well defined with nearly constant dimensions out to the 50 km distance (Figure 4-11).

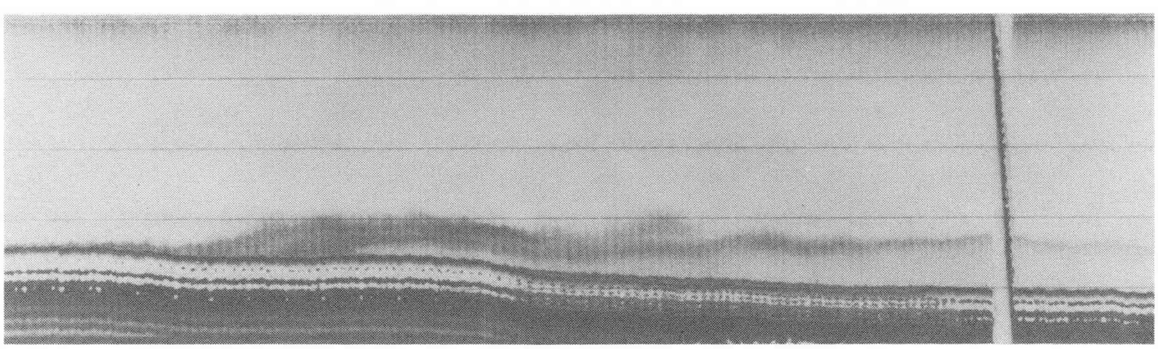
Figure 4-12 presents a cross section made at about 100 km downwind of the plant. The plume, shown in Figure 4-12(a) remains tilted upward toward the north [compare with Figure 4-11(b)]. The plume intersects the ground level over a fairly long distance. Figure 4-12(b) shows a very dense aerosol layer north of the plume cross section extending above the maximum height displayed on the facsimile plot. This layer probably resulted from earlier emitted plume particulates. The aircraft altitude was increased from 10,000 to 12,000 ft (above sea level) and a heading of 255° was taken toward California. Figure 4-13 presents an aerosol cross section that nearly parallels the wind direction. The terrain clearly restricts passage of the hazy air mass that may have resulted from the Four Corners emissions. Therefore,



(a) 18.5 km SOUTH OF PLANT, 1853 MST, 1.06 μm, 233° TRUE COURSE



(b) 18.5 km SOUTH OF PLANT, 1859 MST, 0.53 μm, 053° TRUE COURSE



(c) 37 km SOUTH OF PLANT, 1843 MST, 1.06 μm, 233° TRUE COURSE

Figure 4-9. ALPHA-1 lidar cross sections of Four Corners Power Plant plume viewed 18.5 km downwind from plant at 1.06 μm and 0.53 μm wavelengths and viewed 37 km downwind from plant at 1.06 μm, 1900 MST, 19 December 1979.

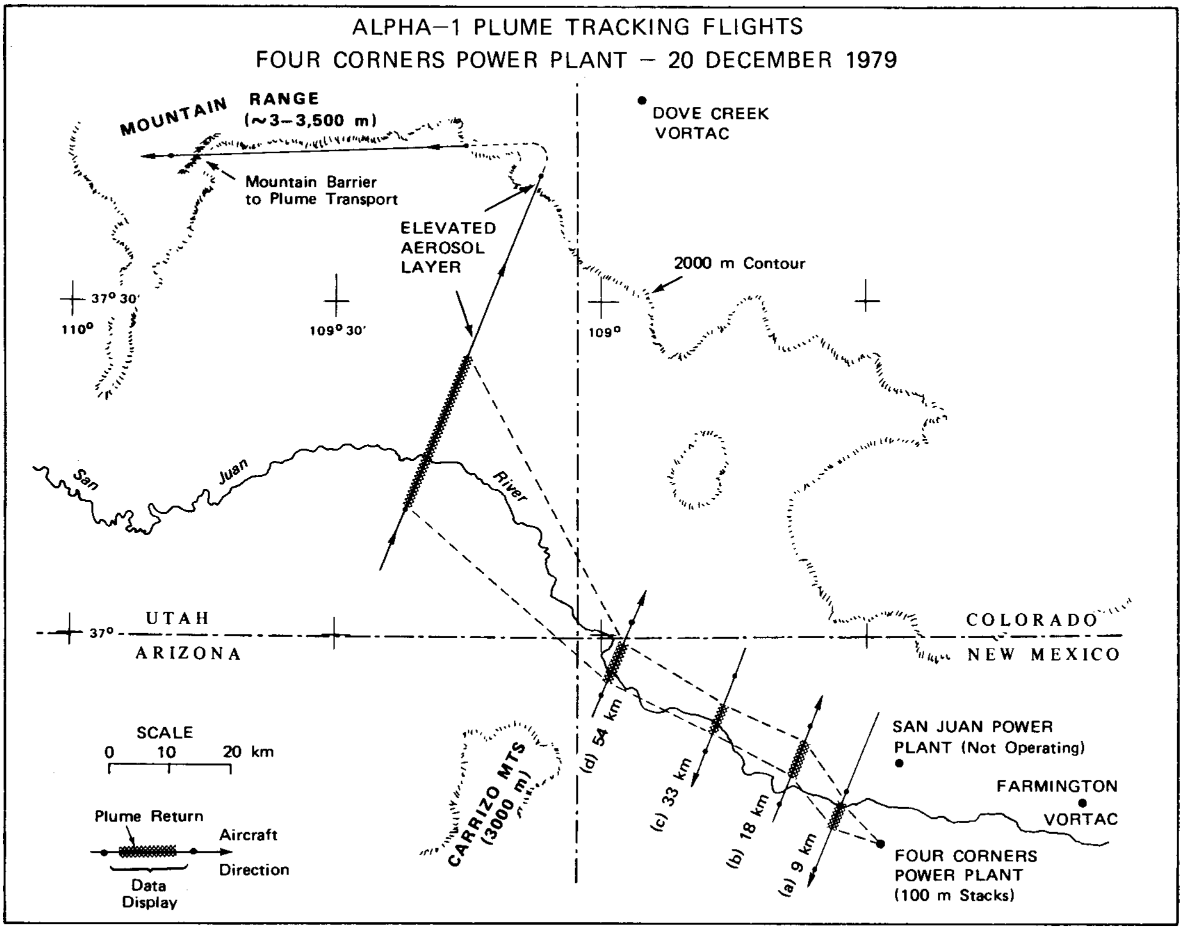
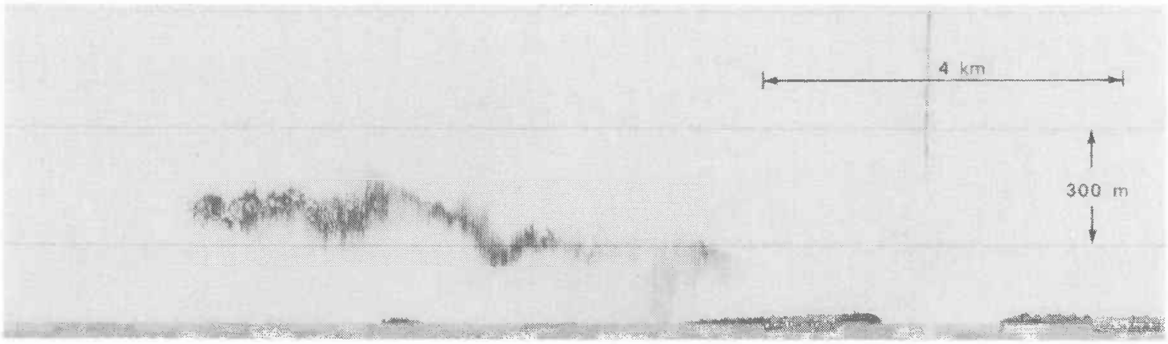
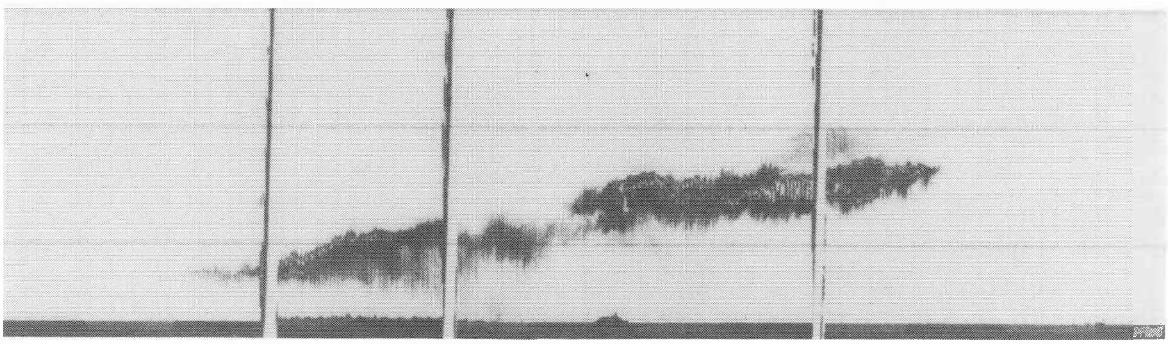


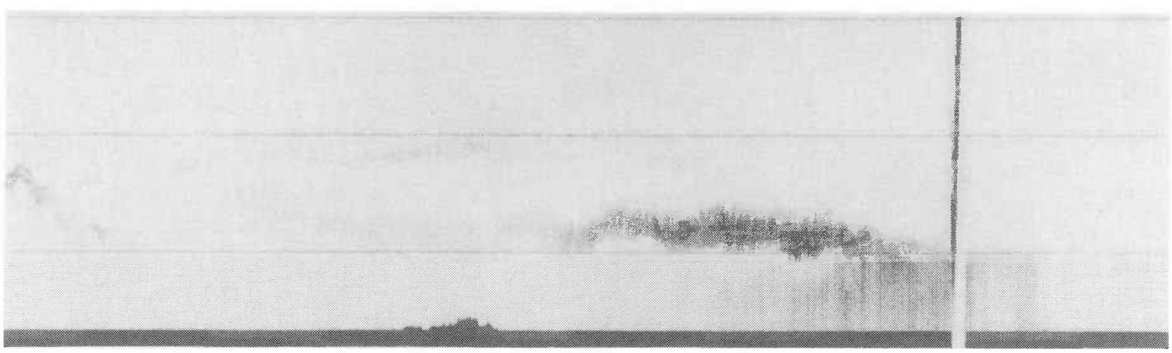
Figure 4-10. Four Corners plant area ALPHA-1 flight paths and locations of plume returns, 20 December 1979.



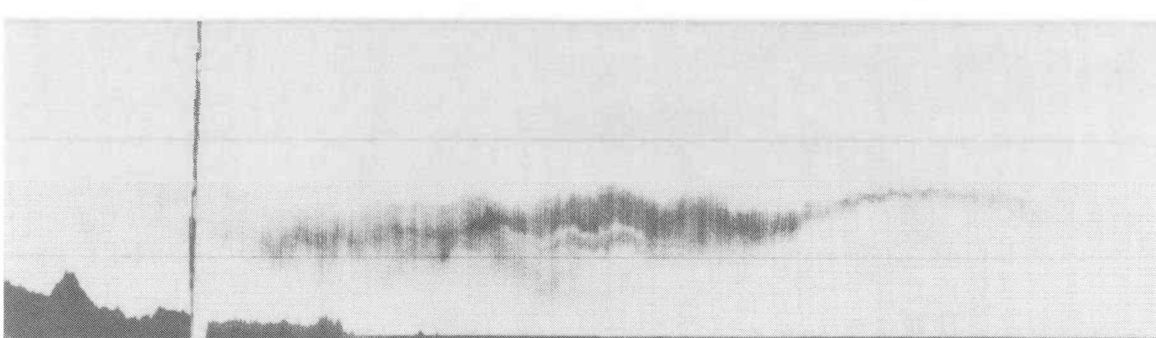
(a) 9 km NORTHWEST OF PLANT, 0955 MST, 203° TRUE COURSE



(b) 18 km NORTHWEST OF PLANT, 1000 MST, 023° TRUE COURSE

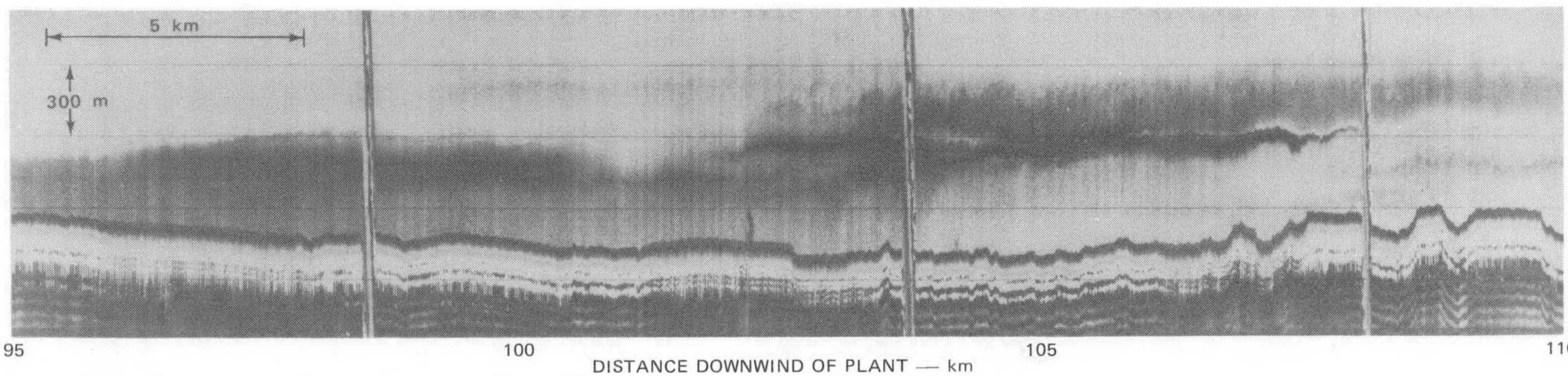


(c) 33 km NORTHWEST OF PLANT, 1006 MST, 203° TRUE COURSE

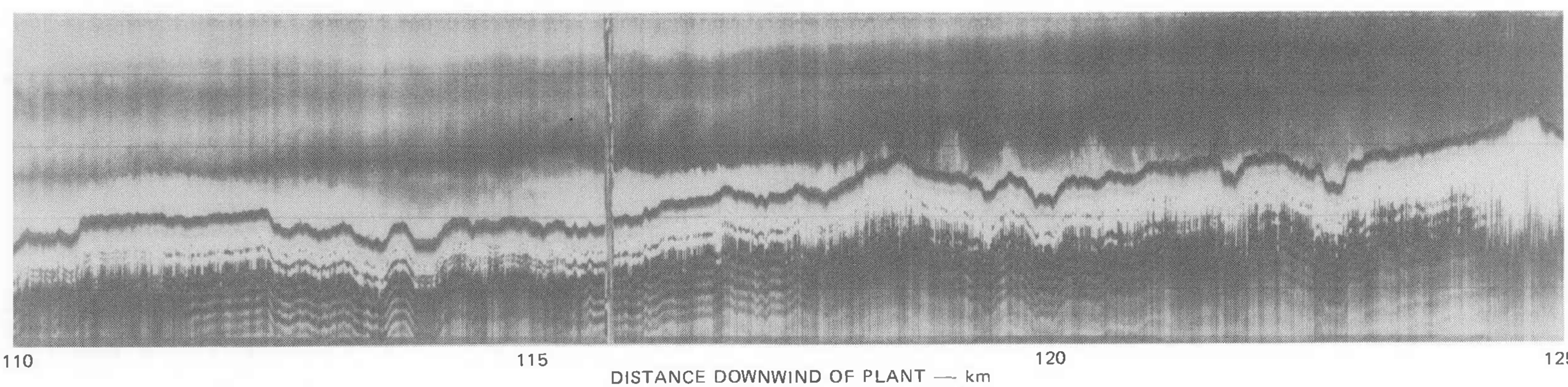


(d) 54 km NORTHWEST OF PLANT, 1016 MST, 023° TRUE COURSE

Figure 4-11. ALPHA-1 lidar cross sections of Four Corners Power Plant plume 9, 18, 33, and 54 km downwind from plant (1.06 μm), 1000 MST, 20 December 1979.

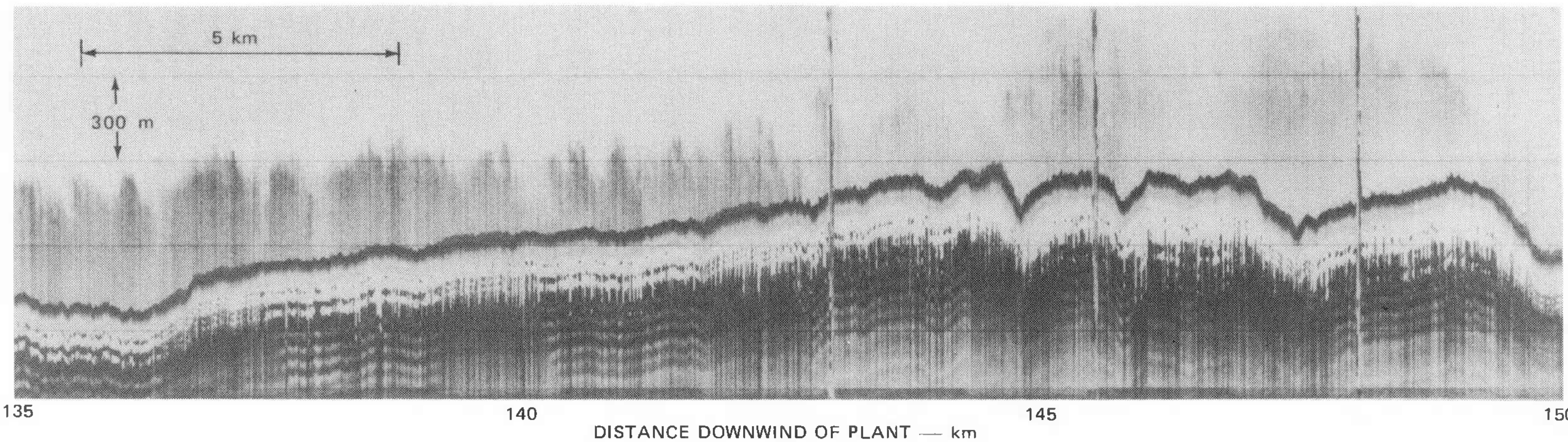


(a) PLUME CROSS SECTION 95 km DOWNWIND, 1053 MST, 023° TRUE COURSE

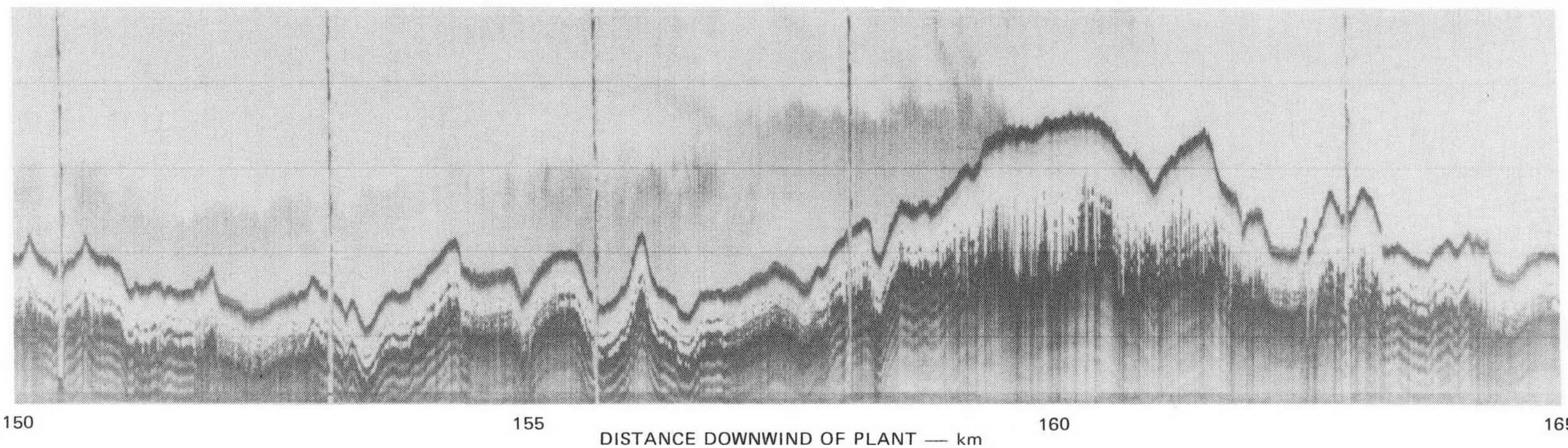


(b) ELEVATED AEROSOL LAYER 110 km DOWNWIND, 1059 MST, 023° TRUE COURSE

Figure 4-12. ALPHA-1 lidar cross section of Four Corners Power Plant plume 100 km downwind from plant (1.06 μm), 1100 MST, 20 December 1979.



(a) MOUNTAIN RESTRICTION TO PLUME TRANSPORT, 1112 MST, 269° TRUE COURSE



(b) MOUNTAIN BARRIER TO PLUME TRANSPORT, 1117 MST, 269° TRUE COURSE

Figure 4-13. Boundary layer structure downwind of Four Corners Power Plant observed with ALPHA-1, (1.06 μm), 1130 MST, 20 December 1979.

ALPHA-1 is an ideal tool to investigate both the structure of power plant plumes and downwind low-visibility hazy air masses. In addition, as further discussed in Section 5, the lidar returns at the 0.53-μm wavelength can be related to optical terms that determine visual range or visibility.

Section 5

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

A two-wavelength airborne lidar system (ALPHA-1) was successfully field tested. Data clearly demonstrate the usefulness of the ALPHA-1 system for observing structure of boundary layers and power plant plumes over large regional areas.

Although a lidar failure occurred during the field program, it was corrected in the field. Recurring problems with computer failures and electrical interferences that seem to be associated with real-time use of the facsimile recorder remain to be diagnosed and corrected.

RECOMMENDATIONS

System Modifications and Additions

Interface of aircraft position sensors with the ALPHA-1 data system is needed before application of ALPHA-1 on environmental field programs. In addition, improved operator and processor control of the lidar operation and facsimile data plotting need attention.

During the field program, numerous desired modifications, each expected to require only a moderate effort, were noted. In addition to these minor modifications, which are not discussed here, we recommend that the following major modifications and additions be incorporated before the first data-collection program.

1. Automatic detector gain control for improved lidar sensitivity.
2. Analog inverse-range squared correction for improved data display.
3. Real-time optical calibration source for continuous monitoring of system performance.
4. Second tape drive for continuous recording, back-up capability, writing of processed results while reading recorded data, and efficient tape copy operations.
5. Extended software for gray-scale and alphanumeric annotation on facsimile records and for improved speed of computational and data handling algorithms.

System Calibration

Amplitude and range response of the ALPHA-1 lidar system has not been evaluated. The range response near the lidar is primarily determined by unblocking of the transmitted laser beam by the coaxial receiver optics. In the far field, the range response is expected to follow an inverse range-squared function. As a minimum effort, the range to which only the inverse range-squared function applies should be determined. If this range is found to be greater than the range to expected useful data, the short-range response of the system will need to be determined.

Amplitude response of the system is necessary in order to estimate the density (even on a relative basis) of particle features such as smoke plumes or the mixed near-surface aerosol layer. The amplitude response can be calibrated by inserting a series of neutral density filters in the receiver as the system has been designed for this calibration. However, since the amplitude response may be a function of detector operating conditions, addition of a continuous calibration method is recommended.

Development of Data Analysis Programs

Boundary Layer and Plume Parameters. The ALPHA-1 atmospheric cross sections shown in this report contain information on: (1) heights of boundary layer particulate matter over large areas and (2) location, height above ground, width, and thickness of pollution plumes as a function of downwind distance from the source. Such information on boundary layer particles and transport and diffusion of plumes during a diurnal period for various meteorological and terrain conditions is currently needed to develop and validate models of plume behavior. In addition, real-time information on plume location and structure provided by ALPHA-1 can be used effectively to direct in-plume sampling experiments.

We recommend that computational procedures be developed to optimize derivation of plume parameters in real-time for operational use. Subsequent computational methods should be developed to refine and extend boundary layer and plume parameters for input to plume behavior models.

Particle Size and Particle Concentrations. The ALPHA-1 system transmits and receives backscattered energy at two wavelengths. The wavelength dependency of backscattered light provides an indicator of size of the scattering particles. Although a detailed size distribution can not be obtained from only two-wavelength data (even with assumptions on particle composition), it may be possible to derive a mean particle size that can be used to compute a backscatter-to-mass concentration ratio--a parameter needed to evaluate particle concentration from backscatter data. We recommend that the information content of the two-wavelength data records be investigated.

Visibility Mapping. One wavelength of the ALPHA-1 system (0.53 μm) is centered near the maximum response of the human eye. Therefore, backscatter data from this wavelength contains information relating to visibility quantities. Visual range is usually expressed in terms of range-integrated extinction coefficient at the visible wavelength. The ratio of observed backscatter at visible (0.53 μm) and infrared (1.06 μm) wavelengths contains information on the backscatter-to-extinction ratio in the visible. This ratio can be applied to ALPHA-1 visible backscatter signatures to derive a three-dimensional field of extinction coefficient. This field of values can then be integrated in any direction to evaluate visual range quantities. Visibility aspects of power plant plumes was demonstrated by the data example shown in Figures 4-12 and 4-13 of this report. In this case, the power plant plume was well defined for a distance of 100 km. At this distance, because of terrain features (shown on the ALPHA-1 data record), a "reservoir" of plume particles was formed resulting in a low-visibility region. Figure 4-13 illustrates the visibility mapping capability of the ALPHA-1 system. In Figure 4-13 the reservoir of visibility reducing particles is seen to be bounded by high terrain features.

We recommend that the application of the two-wavelength ALPHA-1 system to visibility studies associated with power plant plumes be further developed.

Section 6

REFERENCES

1. W. B. Johnson and E. E. Uthe, 1971: Lidar Study of the Keystone Stack Plume. Atmos. Environ., 5, 703-724.

2. E. E. Uthe, F. L. Ludwig, and F. P. Pooler, 1979: Lidar Observations of the Diurnal Behavior of the Cumberland Power Plant Plume. Proceedings of the Annual Meeting of the Air Pollution Control Association, Accepted for publication in J. of APCA.