NOAA Technical Memorandum ERL WPL-78

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

FIELD MEASUREMENTS IN SUPPORT OF DISPERSION MODELING IN COMPLEX TERRAIN — ANNUAL REPORT (1980)

Wynn Eberhard

Wave Propagation Laboratory
Boulder, Colorado
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Administrator

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NOTICE

FIELD MEASUREMENTS IN SUPPORT OF DISPERSION MODELING IN COMPLEX TERRAIN — ANNUAL REPORT (1980)

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ABSTRACT

The EPA is engaged in a concerted effort to develop models for prediction of air quality in complex terrain. Remote sensors and an instrumented aircraft from the Wave Propagation Laboratory and other elements of NOAA's Environmental Research Laboratory are participating with EPA in a series of field experiments that are necessary for development and validation of such models. A calibrated particulate-mapping lidar with multi-wavelength capability is the principal remote sensor. NOAA's accomplishments during the first funding year (February 1980 - January 1981) under the EPA-NOAA Interagency Agreement for Energy and Environment are 1) participation by lidar and other sensors in EPA's Small Hill Impaction Study #1 studying plume impingement on elevated terrain, 2) preliminary experiment by instrumented aircraft on power plant plumes near Farmington, New Mexico, 3) lidar participation in DoE's 1980 ASCOT experiment investigating nocturnal drainage flows in mountainous terrain, and 4) improvements to the lidar for plume-mapping applications.

1. INTRODUCTION

The existing data base, primarily from experiments over uniform terrain, is not adequate for prediction of ambient concentrations of air pollutants released from power plants and other sources in complex terrain (AMS, 1978). The Environmental Protection Agency (EPA) has commenced a major effort to develop verified ready-to-use models for prediction of air quality under such circumstances (Holzworth, 1980). The research is proceeding along three interconnected tracks, namely laboratory simulation (wind tunnel and towing tank), computer model development, and validation from field experiments incorporating a variety of meteorological sensors and tracer analysis techniques. EPA has awarded a contract to Environmental Research and Technology, Inc. (ERT) to develop the models and validate them with data from the experiments.

As part of this major research effort, the Wave Propagation Laboratory (WPL) is cooperatively participating in EPA-sponsored and other field studies designed to promote the understanding of transport and dispersion of pollutants in complex terrain and to provide data of adequate quality for model validation. A unique complement of NOAA equipment and expertise is utilized to measure transport and dispersion of particulate tracers as well as meteorological parameters that affect dispersion in an important way.

WPL and ERL activities in this research program during 1980 can be classified into four major projects. The most important was joint participation by lidar, FM-CW Doppler radar, and acoustic sounders in the EPA-sponsored Small Hill Impaction Study #1 at Cinder Cone Butte (CCB), Idaho, studying plume impingement on elevated terrain. Another project was a preliminary experiment by instrumented aircraft on the constituents and behavior of plumes from the Four Corners and San Juan power plants near Farmington, New Mexico. ERT has suggested this as a candidate site for a future intensive field experiment examining plume impingement on terrain on a larger scale than CCB. A third project was participation by the lidar in the September 1980 ASCOT (Atmospheric Studies in Complex Terrain) experiment sponsored by DoE to study nocturnal drainage flows. This contribution was performed at nominal cost to DoE within the framework of lidar plume research established under the EPA-NOAA interagency agreement. The fourth project pertains to improvements to the WPL lidar for plume-tracking applications by substantially increasing the laser pulse repetition rate for better temporal and spatial coverage of plume behavior. A concomitant improvement is being made in data processing equipment and procedures to handle the enormous volume of data generated by the lidar.

Following a description of the NOAA equipment involved in these projects, accomplishments through January 1981 are given.

2. DESCRIPTION OF INSTRUMENTS

Within WPL are a number of instruments, particularly remote sensors, that are worthwhile in dispersion field studies. The only ones listed here are those involved in experiments during the reported period.

1) Lidar — The WPL lidar (or laser radar) monitored the behavior of oil fog plumes in both the CCB and ASCOT experiments. Operating specifications of the lidar are listed in Table I. Explanations of lidar operation are available in Collis and Russell (1976) and Johnson and Uthe (1971). The lidar is routinely calibrated to provide an absolute measurement of backscatter coefficients of both the clear air and the plume.

Table I.--WPL Lidar Operating Characteristics

Pulse energy (.6943 µm)	1 J
Pulse energy (.3472 µm)	.3 J
Spatial resolution (along beam)	7.5 m
Beam divergence (full angle)	1 mr
Scan domain	upper hemisphere
Scan resolution	0.1°
Receiving telescope	Newtonian, 70 cm diameter
Photomultiplier detectors	EMI 9658
System gain control	Receiver optical filters, PMT voltage
Signal processing	Linear, Biomation 8100
Data recording	Digital magnetic tape through NOVA 840 computer

The ruby laser transmitter emits radiation in its fundamental (.6943 µm wavelength) mode and also in the frequency-doubled (.3472 µm) mode if desired. The longer wavelength (in the red portion of the visible spectrum) is usually superior for plume measurements because the plume signal has greater contrast against the signal from the aerosols and molecules of the clear air than at the shorter wavelength (in the ultraviolet). The longer wavelength also penetrates denser plumes to a further extent. However, since the ultraviolet radiation is considerably more eye-safe, it was utilized with the red output largely blocked during the ASCOT and most of the CCB experiments. This is believed to be the first instance of plume tracking by ultraviolet lidar as part of a comprehensive field experiment.

Data are recorded on digital magnetic tape for later processing and analysis. The signal is also displayed in real time for evaluation of the progress of the experiment.

2) Instrumented aircraft — An Aero Commander 680E operated by ERL/Air Resources Laboratory carried a diversified instrument package for measurement of gaseous constituents of plumes (SO_2, NO_x, O_3) plus aerosol size distribution and light scattering coefficient. Temperature and humidity sensors were mounted for profiling during ascent and descent. An infrared radiometer indicated surface temperature gradients as well as positions of plumes with heavy mass loading. A radar altimeter profiled the underlying terrain to help pinpoint aircraft position to higher accuracy than could the radio navigation equipment alone. Raw data were recorded on digital magnetic tape with output of selected instruments also displayed on strip chart recorders for real-time evaluation. A mobile ground support station measured winds with an anemometer and also double-theodolite tracking of pibals. It also measured temperature and concentrations of O_3, O_2, and aerosols.

3) FM/CW Doppler radar — The Frequency-Modulated, Continuous-Wave radar with Doppler capability is a new remote sensor undergoing evaluation at WPL. Density and humidity variations on the scale of 5 cm in the planetary boundary layer serve as clear-air targets, as can insects and hydrometeors when present (Richter, 1969). In the non-Doppler mode the radar produces information on the vertical stability and turbulence structure of the atmosphere similar to the acoustic sounder but with better vertical resolution. More importantly, the radar in the Doppler mode provides range-resolved measurement of the axial air velocity (Chadwick et al., 1976). Scan and data-processing techniques are available by which profiles of turbulence magnitude, energy dissipation rates, and the area-averaged horizontal wind vector can be determined. Data are recorded on digital magnetic tape for later processing and analysis. Averaged data are also displayed in real-time.

4) Acoustic sounders — Density inhomogeneities of the atmosphere are targets that provide information on the vertical profile of stability and turbulence, such as height of the mixed layer (Brown and Hall, 1978). More complicated layered structures are often revealed in stable conditions. Data are recorded on facsimile charts.

3. CINDER CONE BUTTE EXPERIMENT

The WPL lidar, FM/CW radar, and two acoustic sounders participated in Small Hill Impaction Study #1, which was sponsored by EPA and conducted by ERT during October and November 1980. Figure 1 shows the butte and the positions of the WPL sensors.

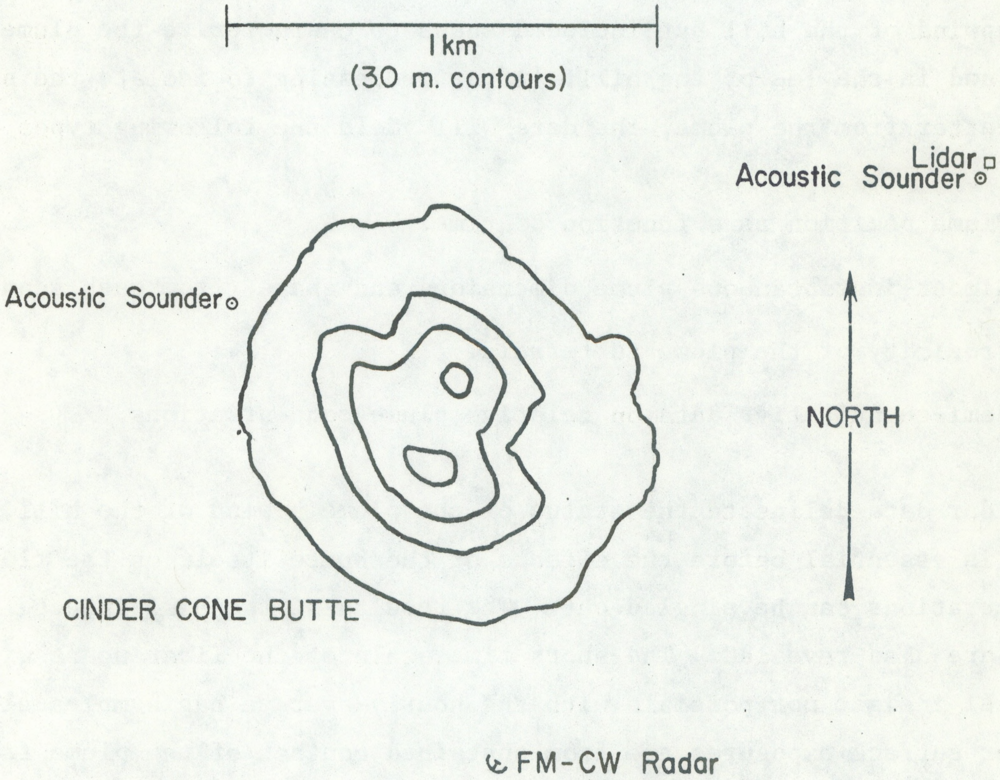

Figure 1.--Location of WPL sensors for the plume impingement experiment at Cinder Cone Butte, Idaho.

The goal of this experiment was to obtain a data set suitable for development and validation of computer models that can adequately predict the behavior of a plume approaching elevated terrain under stable conditions, including surface exposures to plume constituents. ERT and subcontractors obtained meteorological data from several levels on a 150-m tower located 2.3 km north of the butte, a 30 m tower atop the southern knob, and four 10-m towers on the hillsides. SF_6 and occasionally a Freon gas were dispensed upwind from the butte from a platform lifted by a tall crane. Bag samples were taken over an array of positions on the hill for later concentration analysis of these gaseous tracers. An oil fog plume was generated from the same platform, usually simultaneously with the SF_6 release, to be tracked by the lidar and to provide flow visualization.

The lidar performed repeated vertical scans to obtain cross sections (or more properly, slant sections) of the plume at various distances downwind of release. The scan pattern, selected in consultation with ERT, emphasized plume measurements just upwind of the hill but included scans to characterize the plume beside or above and in the lee of the hill. After processing to isolate the signal due to backscatter from the plume, the data will yield the following types of information.

1) Plume position as a function of time.

2) Almost-instantaneous plume dimensions and shape (from each scan).

3) Proximity of the plume to terrain.

4) Semi-quantitative data on relative plume concentrations.

The lidar data delineate the status of the plume upwind of the hill, knowledge of which is essential before the effects of the butte itself on the flow and surface concentrations can be singled out. The results of the hill-induced flow perturbations are also revealed. The short time scale of the lidar scans will also yield physical insight not possible with the hourly-average bag samples alone, e.g., on whether surface exposures are from sustained contact of the plume fringe or intermittent bursts of high concentrations.

During the experiment, maps in plan view of plume position like that shown in Figure 2 were manually drawn using information from the signal display. These maps give guidance both in the field and during later data processing.

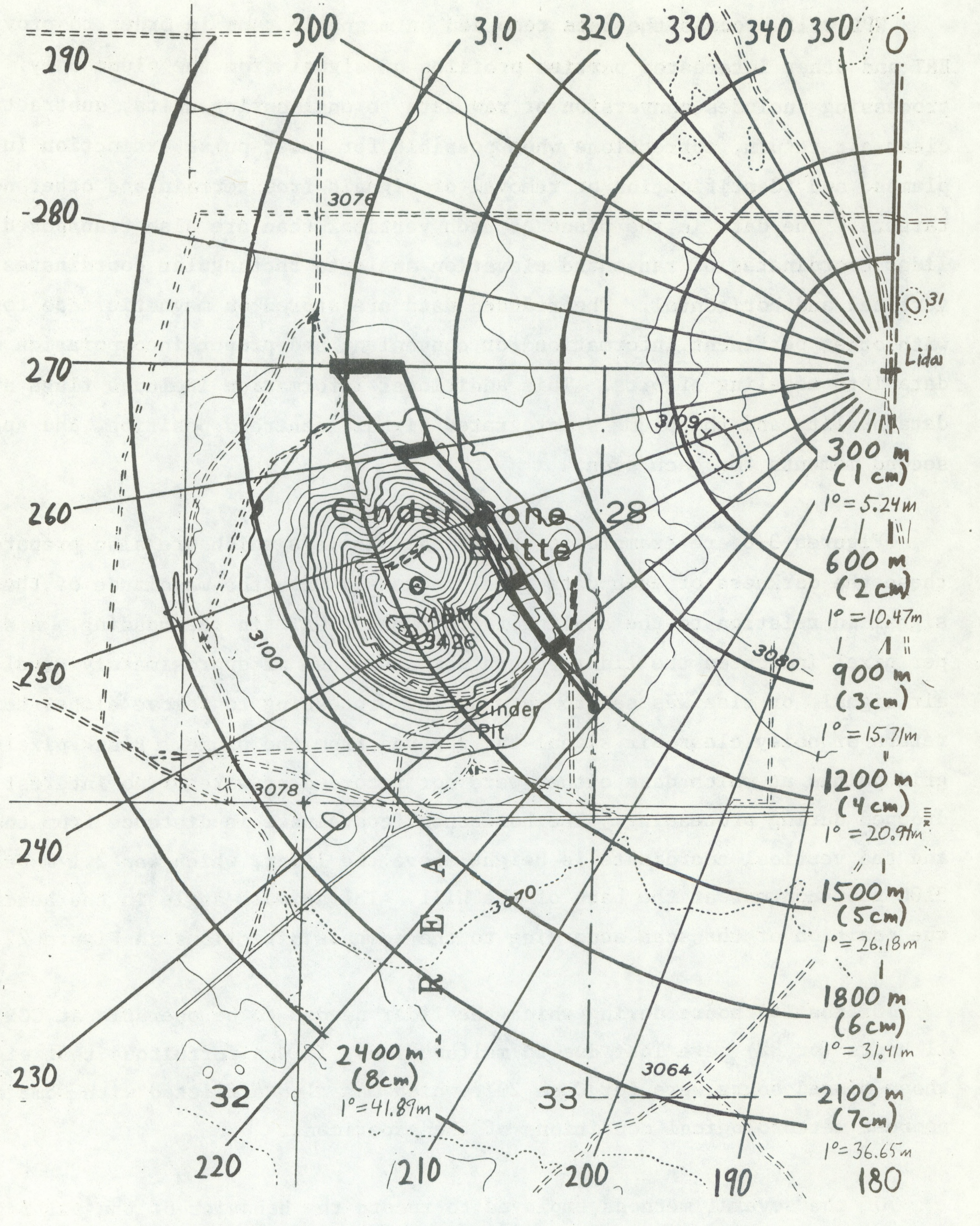

Figure 2.--Example of a plot of plume position and width drawn by hand during lidar data acquisition. Data is for Case 206, Julian date 298, 0305-0327 MST. On the right margin for each concentric circle are three scaling parameters. The first is distance from the lidar, while the other two aided in translating the information in the lidar data display to the plot.

WPL will process the data recorded on magnetic tape in order to provide to ERT and other interested parties profiles of signal from the plume only. The processing includes conversion of raw data to engineering units, subtraction of clear air return, corrections when possible for laser pulse extinction in dense plumes, and identification or removal of signals from terrain and other nonplume targets. The data in the plane of each vertical scan are also transposed from the lidar coordinates of range and elevation angle to rectangular coordinates in the vertical and horizontal. The reduced data are stored on magnetic tape together with other pertinent information for convenient and proper incorporation of the data into modeling efforts. This additional information includes flags specifying data quality and the plume's integrated signal, centroid position, and spatial second moments for each scan.

Figures 3-6 are examples of graphical displays which are also prepared. In these the darkness of each data pixel increases with the magnitude of the lidar signal in relation to the scaling factor "MAX BSCAT" in the heading. A single dot per pixel indicates the lidar return was less than or approximately equal to clear air signal, or else was set to zero during processing to remove either terrain return or noisy clear-air signal far removed from the plume. Blank pixels indicate grid points at which data either were not recorded or were of no interest and were dropped during processing. The horizontal coordinate is distance from the lidar, and the vertical coordinate is height above the lidar, which was 2.1 m below the 3100-foot contour at the base of the hill. The azimuth angle in the heading gives the position of the scan according to the compass directions in Figure 2.

Of the 144 hours during which the lidar needed to be operable at CCB, only 11 hours (or 8%) were lost due to malfunction. It was fortuitous that eight of those missed hours were for Case 207, which was also afflicted with some of the poorest meteorological conditions of the experiment.

Of the several methods employed to record the behavior of the oil fog plume, the lidar was the most precise and consistent. An attempt to traverse the plume with several integrating nephelometers suspended in a vertical line from a crane was largely a failure. During daylight, ground-based photography was informative but mainly only qualitative. Nighttime photography with the aid of a searchlight

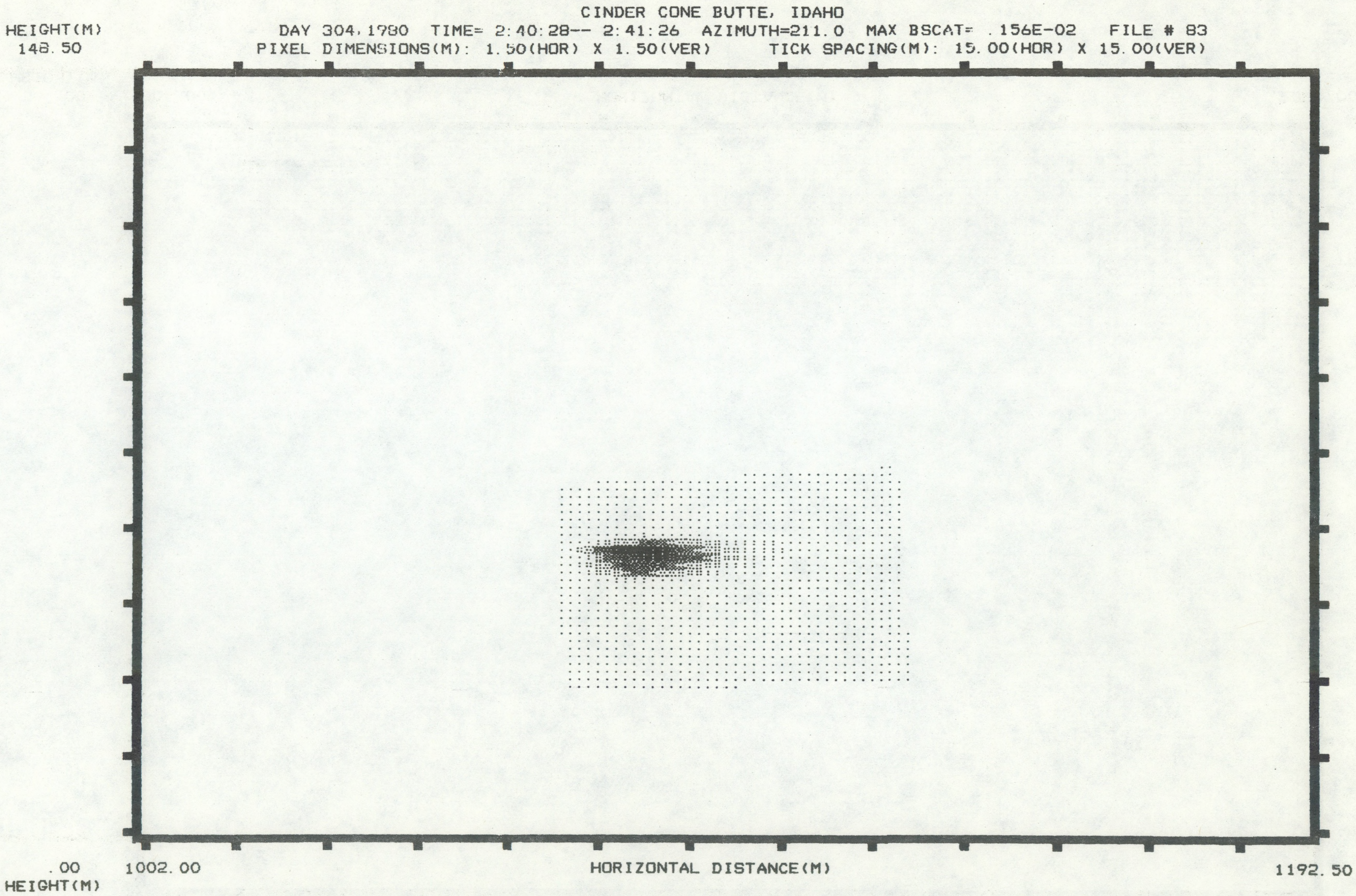

Figure 3.--Lidar signal from a compact, symmetrical plume upwind of Cinder Cone Butte. See the text for a description of this type of plot. Oil fog release was at (see Fig. 2) 196.1° azimuth, 1044 m horizontal, and 53 m vertical distance from the lidar.

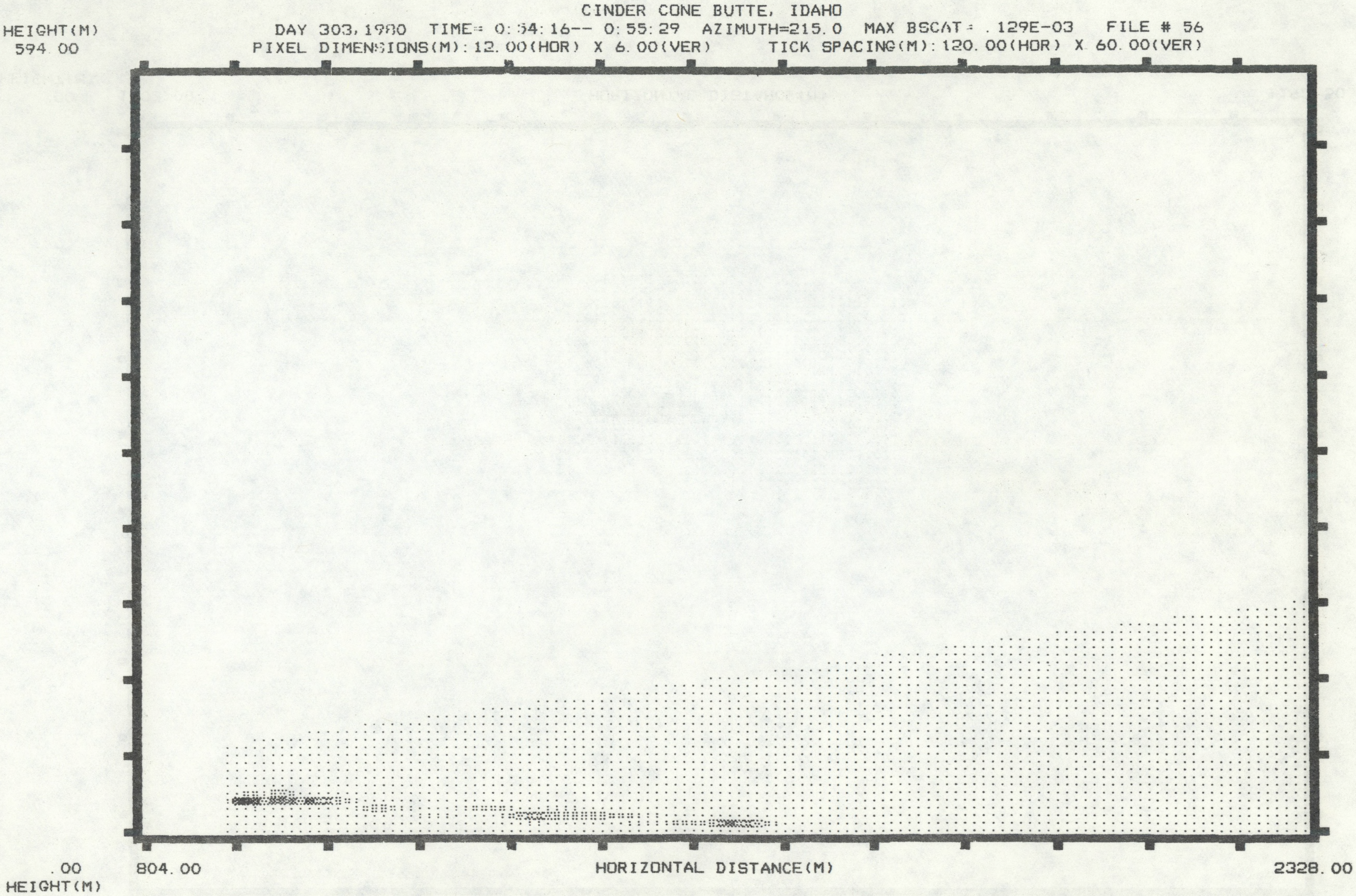

Figure 4.--Lidar signal from a plume distorted by strong wind shear. Oil fog release was at 201.4° azimuth, 850 m horizontal, and 26 m vertical distance from the lidar.

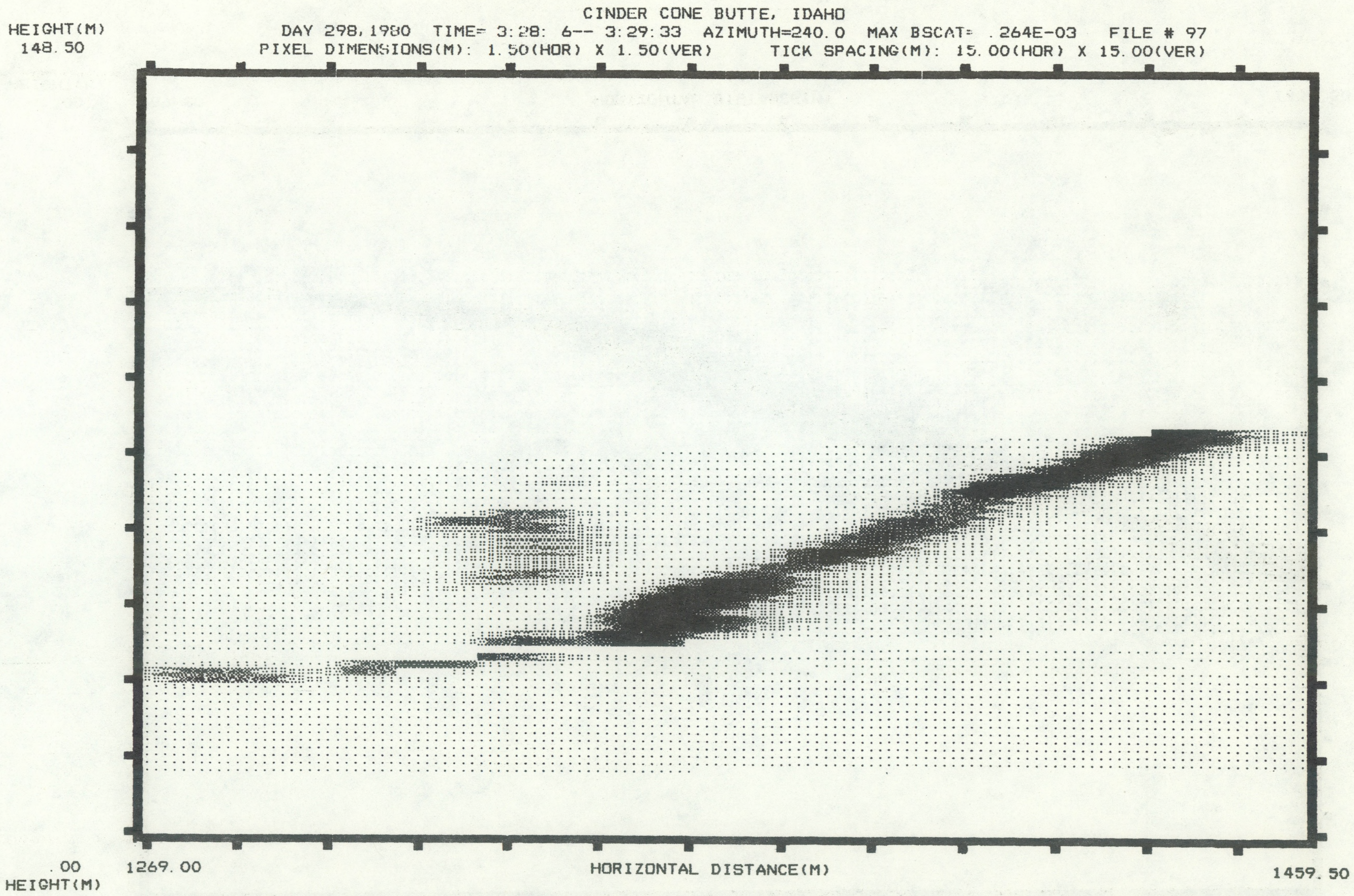

Figure 5.--Example of a plume slightly separated from the butte. The plume appears to the left and above the strong terrain signal from the hillside, which slopes from lower left to upper right. Oil fog release was at 220.6° azimuth, 1194 m horizontal distance, and 32 m vertical distance from the lidar.

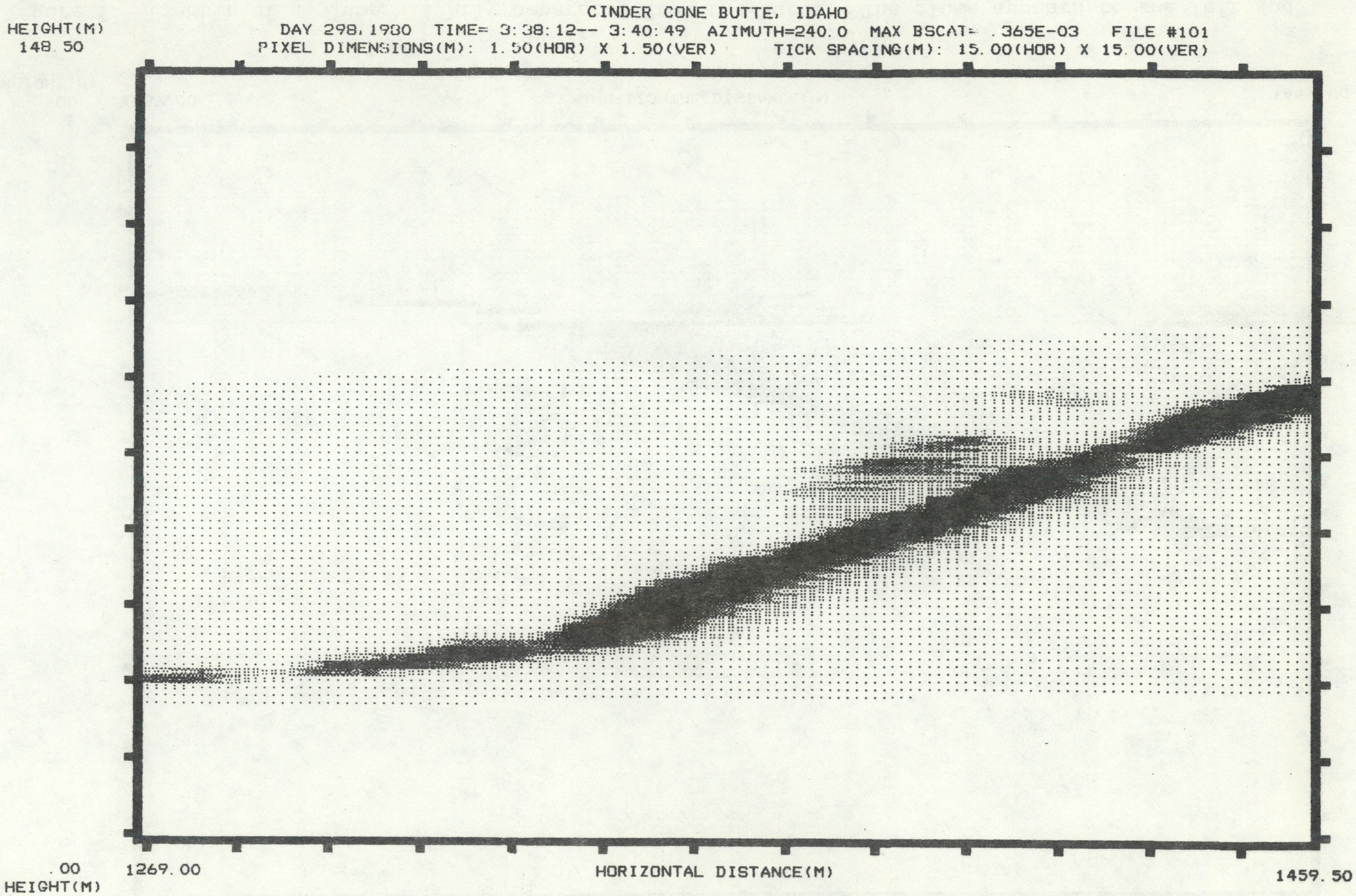

Figure 6.--Example of a plume contacting the butte. Compare with the scan in Fig. 5, which was made 10 minutes earlier for the same plume release coordinates.

was even more limited. Photography with ultrasensitive equipment through a window in the cabin floor of an airplane circling overhead was possible under certain lighting conditions, but determining the position of the plume relative to the butte from the photographs is often very difficult. The principal disadvantages of the lidar data were the limited scan rate, the lack of data from the region hidden from view by the hill, and the interval of time after the experiment required for processing.

Involvement of the FM/CW radar was primarily to evaluate and demonstrate the capabilities of this new remote wind sensor in complex terrain diffusion research and secondarily to acquire data useful to the modeling effort. Some interesting events were recorded in all of the operating modes mentioned in the equipment description. Just after the conclusion of the experiment some of the computer equipment and the log book for the experiment were stolen from the locked instrument trailer in spite of the presence of a security guard at the CCB site. These items were not recovered, but the data are still available on the untouched magnetic tapes. Nevertheless, the loss has severely hampered analysis of the radar data. Some progress was made in reconstructing the log book from the tapes. Since the data analysis hardware could not be immediately replaced, it was necessary to convert to less efficient methods on other WPL computers. Because of more pressing commitments in other projects, analysis of the radar data from CCB has been postponed. It is anticipated that the data will later be examined to illustrate the potential of this specialized radar for dispersion research in complex terrain.

The acoustic sounders were operated principally to explore the potential of these remote sensors in complex terrain diffusion research. Of main interest is the characterization of the vertical atmospheric structure in the lee of the terrain compared with a region of unperturbed flow. As the attention of research progresses to more complex terrain and wake effects, acoustic sounders as well as the FM/CW radar may become essential components in the network of instruments required to describe atmospheric dynamics in three-dimensional space and time. A secondary goal for the acoustic sounders was to aid in understanding the evolution of the air flow and stability regime at CCB. The acoustic sounder group at WPL will investigate the facsimile records from CCB for illuminating events after ERT provides wind data needed for the interpretation.

4. PLUME EXPERIMENT AT FARMINGTON, NEW MEXICO

The instrumented aircraft completed 50 experimental flight hours during October and November 1980, studying the behavior and constituents of the plumes from the Four Corners and San Juan power plants. The goals were to assess the suitability of the site for a later intensive plume impingement experiment and also acquire data for case studies of plume response to terrain features.

The San Juan plant with 120-m stack height is located 15 km north and slightly east of the Four Corners plant, which has 75-m and 90-m stacks. The Hogback Mountains form a discontinuous ridge roughly parallel and 5 km west of the line between the power plants. The Mesa Verde area of the Rocky Mountains to the north offers a possibility of plume impingement on terrain substantially above effective plume height.

During the experimental period the mean flow in stable conditions was usually easterly and rarely southerly, which may be attributed to drainage flow in the region. The visible plumes cleared the Hogback ridge with the possible exception of emissions from the shorter Four Corners stacks on occasion. During the single period of measurements for southerly flow the plumes from the two plants merged and apparently veered to the west of the higher terrain. It is concluded that this site is poorly suited to an intensive field study of impingement of the plumes from the power plants. On the other hand, it is an attractive site for investigation of impingement on the Hogback ridge from a lower release.

Other observations of interest were made. Photographs of the plume reveal the wavelength of its vertical oscillation induced by the flow over the Hogback ridge. There was also evidence of ridge-induced turbulence on plume dispersion in some cases. With temperature and wind profiles also available it should be possible to compare these observations with those expected on the basis of theoretical considerations. The integrating nephelometer showed that particulate loading of the Four Corners plume is more than adequate for lidar tracking, but the San Juan plume would be difficult to detect beyond a few kilometers downwind of release. The plumes could be differentiated by the instrumented aircraft even as they began to merge by the difference in their ratios of aerosol to SO_2 loading.

5. ASCOT EXPERIMENT

The plume-mapping lidar also joined the September 1980 ASCOT experiment studying nocturnal drainage flow in the mountainous terrain of the Geysers area near Middletown, California. Figure 7 shows the location for oil fog releases, each of one-hour duration, from the side of the Anderson Creek ravine. The lidar's position at the mouth of the valley is also shown. A sequence of vertical scans of the lidar reveals the progress down the valley of the front of the plume. Two example scans are in Figures 8 and 9. The later spatial and temporal evolution of the plume within a few kilometers of the lidar was also monitored. A gaseous tracer (perfluorocarbon) was dispensed from the same location as the oil fog and sampled at an array of ground stations and also vertically profiled at one location by other scientists. The lidar signals from the oil fog will be compared with the perfluorocarbon concentrations in an effort to improve descriptions of the transport and dispersion.

6. LIDAR IMPROVEMENTS FOR PLUME MAPPING

One phase of this project is an improvement in the lidar's design and methods of data analysis to better serve the aims of dispersion experiments in complex terrain. In WPL's original proposal, the first year was allocated to system upgrade in preparation for a field experiment during the second year. Since the CCB experiment was scheduled during the first year, the engineering activities must be spread over a longer time, and the lidar was required to operate at CCB without benefit of most of the new features. During the reported period a systems analysis was performed, design goals established, and procurement completed of the principal components of equipment.

A major limitation of the original system is the scan rate which in practice is approximately 30 vertical scans per hour maximum. A frequency-doubled Nd:YAG laser with maximum pulse rate of 10 s^{-1} was chosen to supersede the ruby laser. This change will allow a tenfold increase in scan rate, which is essential in fully describing plume behavior in complex terrain. Whereas the old system can at best scan a plume at each of five distances downwind only once every ten minutes,

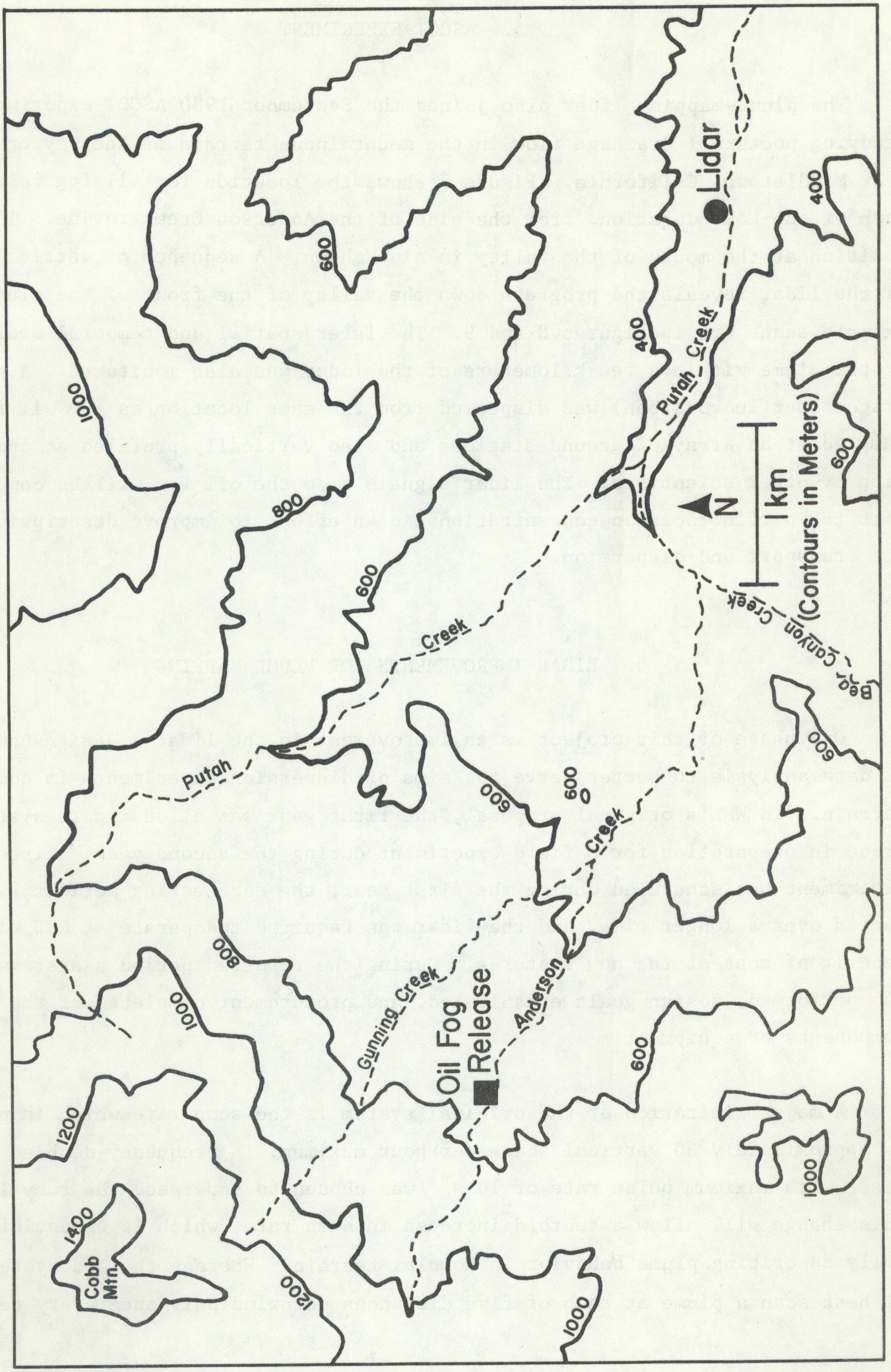

Figure 7.--Location of lidar and oil fog release at the 1980 ASCOT experiment.

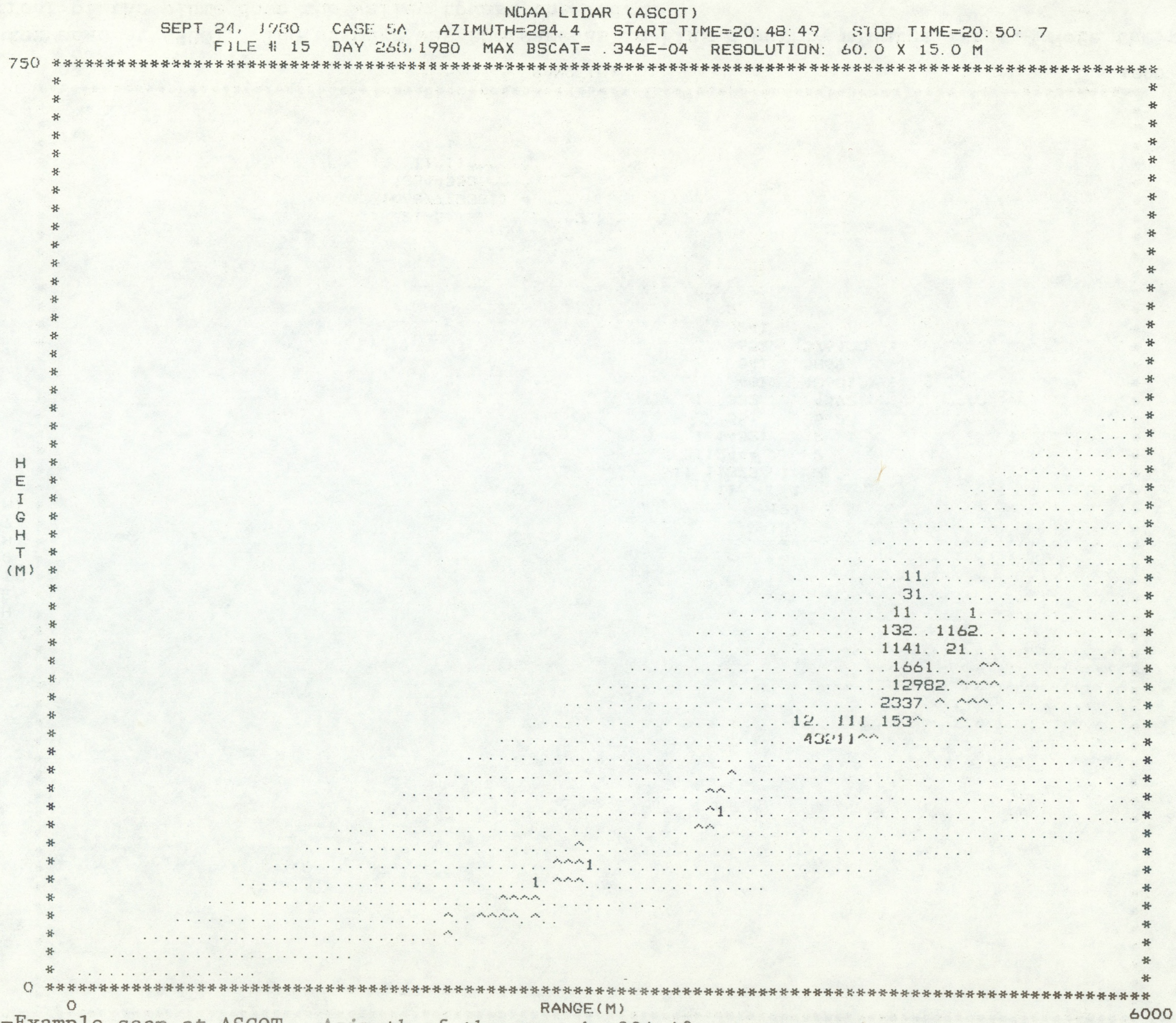

Figure 8.--Example scan at ASCOT. Azimuth of the scan is 284.4°, which passes approximately 100 m south of the oil fog release point. Plume release commenced 20 minutes earlier. Circumflexes show the locus of the terrain signal obtained at another time. Dots show where valid signal no greater than the clear-air return was received. The numbers give the magnitude of the plume signal relative to the scaling factor "MAX BSCAT" listed in the heading. The vertical scale is expanded by four times the horizontal.

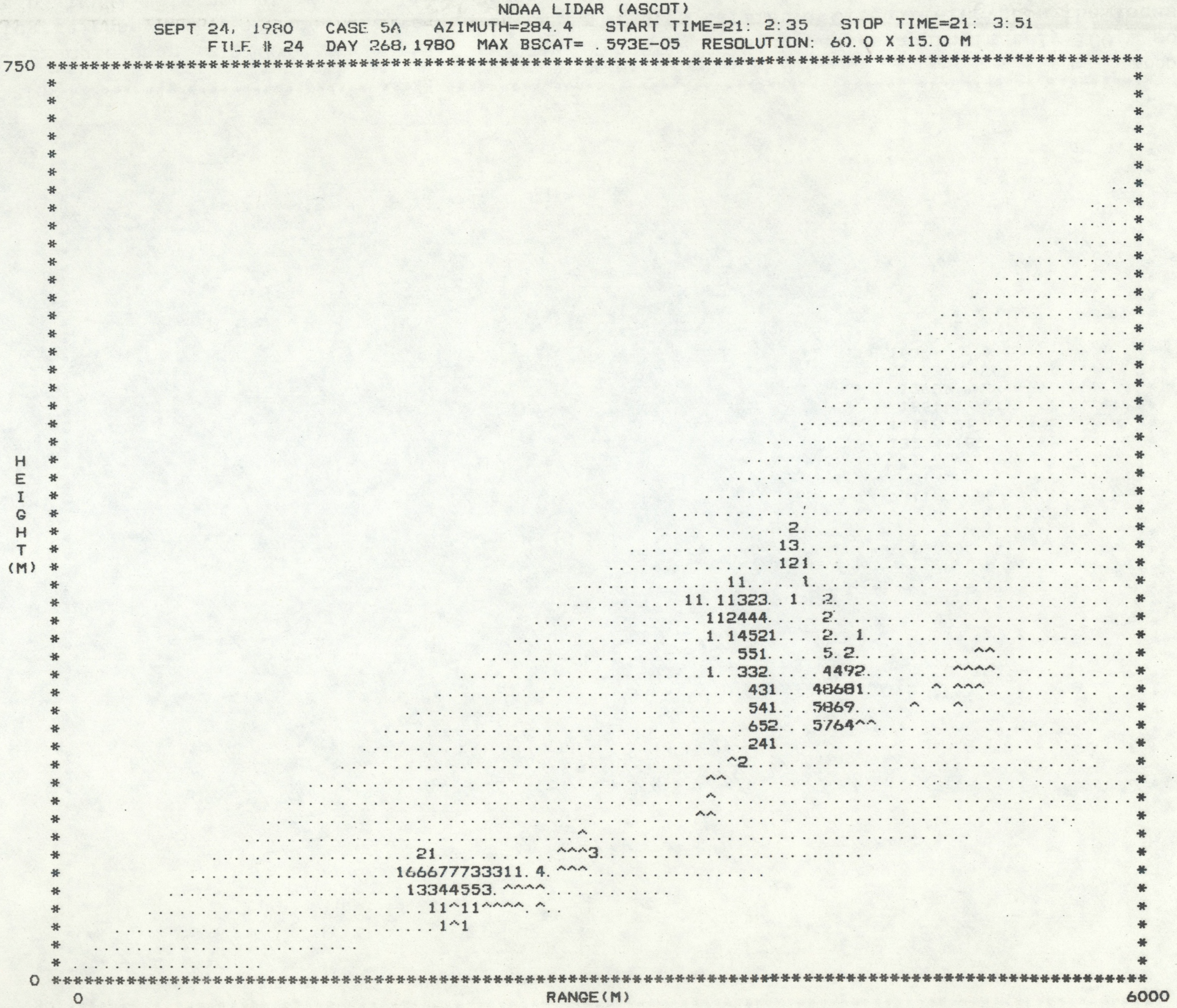

Figure 9.--Later scan at ASCOT. The azimuth was the same as in Fig. 8 but 14 minutes later. Note the progress of the front of the plume down the valley toward the lidar.

the high-repetition rate lidar will provide ample coverage of the plume in space and time. An automatic scan control system will replace the earlier manual version to take full advantage of the quicker pulse rate.

Past field experience has shown that redundancy is needed in a lidar system to maintain nearly 100% operational status during intensive field experiments like those conducted in this project. Hence the old laser and computer will remain installed as backups with limited but useful capabilities in case of major failure of the new, faster laser or computer. The old laser will also be available for other types of experiments to which it is better suited, and the old computer will normally be dedicated to generating graphical displays of selected events such as in Fig. 2.

Techniques for processing the lidar data were also targeted for significant improvement. The algorithms for precise quantitative data reduction had for the most part already been developed and tested at WPL. However they were not yet cast into a form suited to rapid reduction of raw data to plume signal in a form convenient to atmospheric scientists. The prodigious average data rate possible with the new laser (as high as 2×10^4 samples per second) will exacerbate this deficiency. The following modifications were therefore planned:

1) Calculate and record in real time the backscatter coefficients in engineering units rather than recording raw data only. A Data General Eclipse computer was procured to handle the computation load.

2) Develop methods to display selected events in near-real time such as plume position and width in plan view and individual plume cross-sections.

3) Design an archival system for the lidar data which is easily used by individuals unfamiliar with details of lidar operation. The archived data will include information designating the quality of the data according to the judgment of the experienced lidar scientists who process it. This task was completed.

4) Produce a second generation of data-processing algorithms which are both faster and more objective while maintaining facility for human interaction in unusual situations. A step in this direction was made by streamlining the existing data reduction algorithms. Planned for the future is automation of some of the algorithms, particularly those used in pulse-by-pulse processing.

Completion of installation and testing of the new equipment and processing procedures is planned for the second year. These improvements will make this the premier lidar for plume mapping with regard to thorough spatial and temporal coverage with high quantitative precision.

7. SUMMARY

Airflow and pollutant dispersion in complex terrain are subjects of both scientific and practical importance which are being researched by atmospheric scientists. Accomplishment of field experiments that provide data adequate for development of dispersion models valid in complex terrain is particularly challenging because of the three-dimensional inhomogeneity of meteorological parameters and resultant irregularity of tracer distributions. Lidar tracking of a plume of particulate tracers is a very useful, or even essential, component of such experiments. WPL's lidar successfully contributed during 1980 to two field experiments studying plume behavior in complex terrain. For EPA's plume impingement research at Cinder Cone Butte the lidar measured plume position and dimensions upwind of the hill and also revealed the effects on the plume of flow perturbations induced by the hill. Acoustic sounders and the wind-sensing FM-CW Doppler radar were also operated there by WPL. At DoE's ASCOT experiment the lidar monitored the behavior of a plume transported down a valley by the nocturnal drainage flow. In a separate endeavor an instrumented aircraft observed the constituents and behavior of power plant plumes near Farmington, New Mexico, in order to evaluate the suitability of this region for a later intensive experiment in plume impingement. Modifications to the lidar are in progress to provide ample coverage of plume dynamics in complex terrain by increasing the maximum sampling rate by an order of magnitude.

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