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DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

CONTRIBUTIONS BY WAVE PROPAGATION LABORATORY TO EPA'S COMPLEX TERRAIN MODEL DEVELOPMENT PROJECT

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Boulder, Colorado
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CONTENTS

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W. L. Eberhard

ABSTRACT. The Wave Propagation Laboratory (WPL) participated in the Environmental Protection Agency's Complex Terrain Model Development Project, whose objective is development of numerical air quality models valid in complex terrain. Particular attention was given to impaction of elevated plumes on high terrain during stable (nocturnal) conditions. WPL joined in experiments at Cinder Cone Butte (also called Small Hill Impaction Study #1), at The Hogback (Small Hill Impaction Study #2), and at Tracy Power Plant (preliminary and main phases of the Full Scale Plume Study). During one or more of these experiments, WPL operated a plume-mapping lidar, acoustic sounders (some with Doppler capability), sonic anemometers, a tethered sonde, and crosswind optical anemometers. Measurements were usually displayed in real time for experimental guidance and later processed with quality assurance for quantitative analysis. A synopsis of data acquisition and archiving is given for each experiment, including a review of the results of scientific analyses already completed. Separate studies at The Hogback with an instrumented aircraft and at the Boulder Atmospheric Observatory with the lidar are also summarized.

1. INTRODUCTION

During the late 1970's the Environmental Protection Agency (EPA) identified a critical need to develop dispersion models valid in complex terrain. The EPA therefore convened a workshop (Hovind et al., 1979) to recommend a program of experiments and model development to fill this void. Holzworth (1980) outlined EPA's consequent plan to develop better complex terrain models with an emphasis on the impaction of elevated plumes on high terrain during stable (i.e., nighttime) conditions. This large, multiyear program is called the Complex Terrain Model Development project (CTMD). A series of annual milestone reports that were prepared mainly by Environmental Research and Technology, Inc. (ERT), which was EPA's primary contractor on CTMD, provide a comprehensive description of all phases of the project. The references are Lavery et al. (1982, 1983), Strimaitis et al. (1983, 1985b), DiCristofaro et al. (1986), and a final report to be completed in the future. CTMD included the integrated components of field studies, laboratory model experiments, and numerical model evaluation and improvement, all steered by the needs of the modelers to achieve a valid and practical model.

Scientists with the Wave Propagation Laboratory (WPL) and other laboratories of the National Oceanic and Atmospheric Administration (NOAA) participated in the workshop. WPL's mission is the invention and improvement of remote sensing techniques for investigating atmospheric phenomena. As part of that mission, WPL engages in collaborative field studies to demonstrate and prove these techniques, as well as to advance scientific understanding of the atmosphere. Since the CTMD field experiments dealt with wind, turbulence, temperature profile, and plume behavior ~100 m above the surface, any pertinent data accessible by remote sensors could contribute significantly to the success of the project. WPL indeed had a major role in acquiring several landmark data sets during CTMD. EPA supplied most of the financial resources under EPA-NOAA interagency agreements running from fiscal year 1980 through 1986. It should be noted that this EPA project also benefitted to a significant extent from the infusion of WPL base funds, which had the purpose of advancing the state of the art in remote sensing equipment and methods of analyzing their data.

This report summarizes WPL's accomplishments during CTMD. The discussion provides a comprehensive list of WPL's activities, data products, results, and publications, but the reader must examine the references to obtain details. Section 2 describes improvements to the plume-mapping lidar, which had a principal role in the field experiments. Section 3 reviews the involvement and results of WPL participation in the individual CTMD field experiments. WPL's lidar joined in additional atmospheric dispersion studies sponsored by the EPA and Department of Energy. These are mentioned in a separate section, because the capabilities gained during CTMD enhanced the contributions to these other programs.

2. ADVANCES IN LIDAR PLUME MAPPING

WPL already had an operating lidar before the inception of CTMD, but the instrument was not well suited to the intensive data rates desired for measuring plume dispersion. Upgrades to the lidar were an important aspect of the first year's efforts. However, the shortness of the interval between initial receipt of funding and the first experiment at Cinder Cone Butte in 1980 prevented installation of most of the improvements until afterwards. In spite of its limitations, the lidar as described by Eberhard (1981b, 1983) did yield valuable data during the first CTMD experiment. The major modifications were all finished before the experiment at Hogback Ridge in 1982, although a few minor refinements came later.

The most significant change was installation of a laser with 10-Hz pulse repetition rate that allowed more rapid scans to cover the plume's behavior adequately in time and space. A new data acquisition system (hardware and software) congruent with the high data rates from the laser was also added. WPL also developed a computer-based automatic scan controller, which allowed editing of scan instructions without interrupting data acquisition. The Stable Plume Experiment at the Boulder Atmospheric Observatory during autumn 1981 and spring 1982 was primarily a shakedown of these newly installed improvements, but the test also produced a useful data set on plume dispersion. Eberhard et al. (1986a) briefly described this improved lidar and the results of its operation. Eberhard and McNice (1986) gave a detailed description of the configuration of the lidar system during the Full Scale Plume Study in 1984.

The development of sophisticated software for processing the lidar data was WPL's second major advance in lidar technology. The data sets were very large ($\sim 10^9$ data points for the 1984 Full Scale Plume Study), which demanded efficient computer processing. However, the raw lidar signals, from which the desired information on the concentration patterns of a light-scattering tracer was sought, were severely contaminated by signals from the nearby terrain and the background haze. Attenuation of the probing light by the haze, and particularly by the plume itself, added a considerable amount of distortion. Our solution allowed a human operator (by means of interactive graphics) to guide the computer's efficient processing of the data, even when some of the contamination was highly variable.

For data acquired during 1980, the operator interacted on a pulse-by-pulse basis to reduce the data, as described briefly by Eberhard and McNice (1982). This approach proved to be unacceptably slow.

Considerable effort was invested during 1981 through 1983 in writing user-friendly software that made possible human interaction on a much more efficient scan-by-scan basis. A package of programs readied the data in a form convenient for scientific analysis. These data reduction procedures are fully described in Eberhard et al. (1986b), which has been submitted for publication in Journal of Atmospheric and Oceanic Technology. Kaimal et al. (1986) also discussed similar procedures that were used in another plume dispersion study.

The products of the processing included the two-dimensional distribution of inferred tracer concentration in the vertical planes of the scans that made cross sections through the plume. In the routine example of Fig. 1, twelve scans during 0600-0700 on August 7, 1984, at lidar azimuth 313.4° are averaged together. The denser part of the plume, as expressed by the optical backscatter coefficient (m^{-1} sr^{-1}), appears as darker/larger pixel symbols. The vertical profile of horizontally integrated concentrations was plotted with zero on the left of the frame and the peak value of 0.127×10^{-1} sr^{-1} touching the right of the frame. The horizontal profile of the vertically integrated plume has zero on the bottom and peak value at the top. The centroid, i.e., center of mass, of the plume is listed at 95.1 m above the lidar and 1908.2 m distance at the scan azimuth of 313.4°. This point was 472.7 m downwind and 58.2 m above the source (stack top) with an average trajectory direction of 76.2°. The standard deviation of the vertical profile yielded the vertical dispersion coefficient of

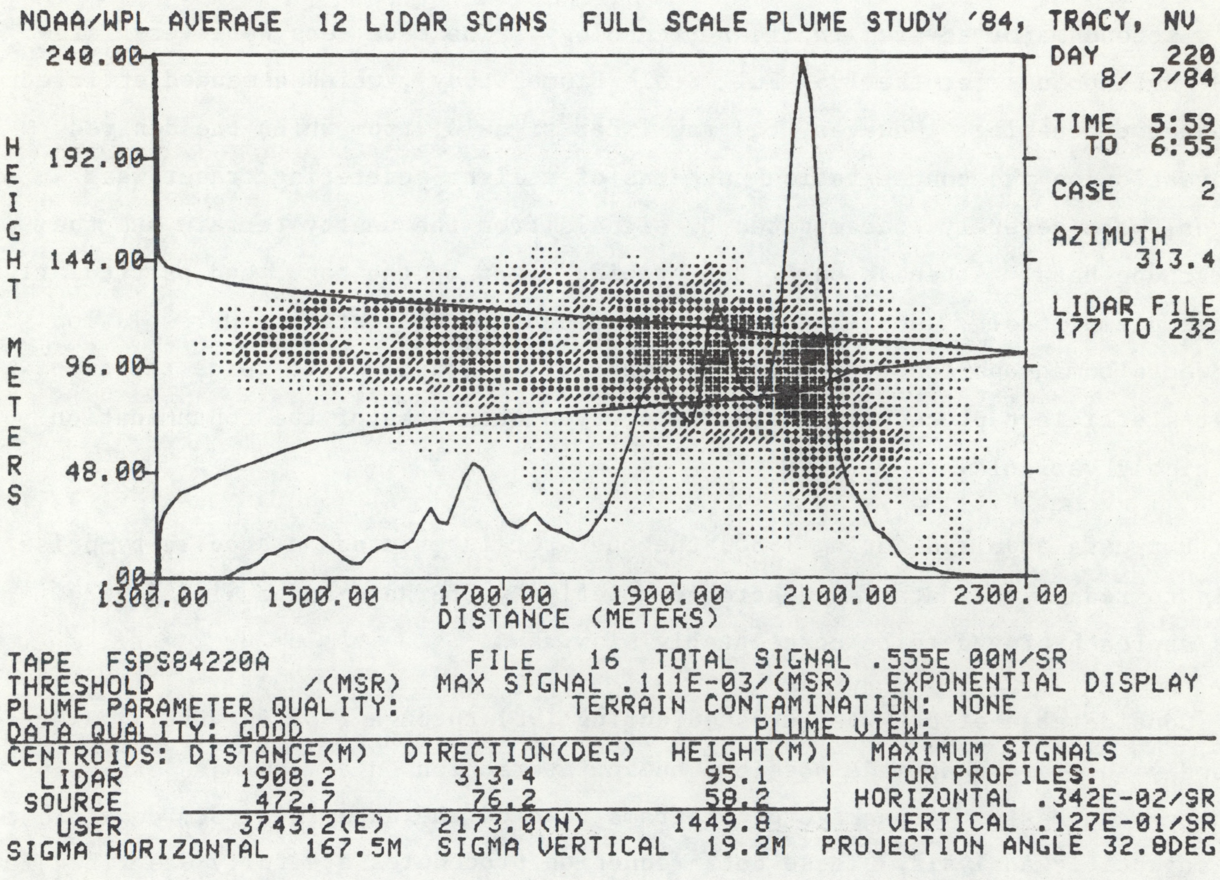

Figure 1. Example of processed lidar data. The vertical scale (height above the lidar) is expanded, compared with the horizontal coordinate (distance from the lidar).

19.2 m. The horizontal dispersion coefficient is obtained from the standard deviation of the horizontal profile (167.5 m) multiplied by the cosine of the projection angle (32.8°), which was the angle between the scan plane and the normal to the plume's axis. Similar graphs and calculations were obtained for the individual scans as well. The time series of trajectory directions showed that a shift in wind direction of approximately 50° during the hour caused the plume's wide spread in Fig. 1. All of this information was archived on digital magnetic tape and in graphs. The centroid positions and dispersion coefficients are also available in printed tables.

3. DESCRIPTIONS OF EXPERIMENTS AND RESULTS

3.1 Small Hill Impaction Study #1

The first cooperative CTMD experiment, called Small Hill Impaction Study #1 (SHIS#1), took place at Cinder Cone Butte (CCB) in the vicinity of Boise, Idaho. Lavery et al. (1982) described the layout of the instrumentation, the progress of the experiment, and some results from preliminary analyses. WPL participated only in the main phase from October 16 through November 12, 1980. CCB is an isolated hill that is roughly axisymmetric. It rises about 100 m above the surrounding plain and has a diameter at the base of about 1 km. The goal of SHIS#1 was acquisition of a data base to test existing and create improved numerical models that predict the surface concentrations of tracers released from an elevated point upwind of a hill of simple topography during stable conditions.

The light-scattering particles in a plume of oil fog provided the tracer for the lidar. The oil fog generator was held aloft by a crane, which was positioned for impaction of the plume on CCB according to the anticipated wind direction. The lidar site was located about 1.5 km from the center of CCB, such that the lidar could view the plume from the side. The lidar performed a sequence of vertical scans at several azimuth directions, which intercepted the plume at various distances downwind of release. Post-processing extracted the range-resolved concentration profile of the oil fog for each pulse. By combining the results from the many pulses in each vertical scan, we determined the two-dimensional distribution of the tracer in the cross section defined by the scan plane. Lynch et al. (1982), Eberhard and Lavery (1984), and Eberhard et al. (1986b) discussed the advantages and problems associated with mapping plumes with lidar using elastic backscatter from tracer particles.

To ensure the eye safety of experimental personnel on CCB, the lidar operated in the ultraviolet with a frequency-doubled ruby laser as transmitter (Eberhard and McNice, 1982; Eberhard, 1983). Only 8% of the experimental hours were lost because of lidar malfunction (Eberhard, 1981b).

The main purpose of the lidar data was to determine the plume's position and growth between the source and the hill. Typically, the scan plane nearest the source revealed the plume's state after the initial effects of buoyant rise and growth created by the generator's hot jet. Another scan plane approximately tangential to the base of CCB defined the plume just before the flow experienced the presence of the hill. A scan plane between these often gave further information about the plume's direction and the progress of the dispersion. Other scans abreast and downwind of the hill revealed the proximity of the plume to the surface (Eberhard, 1981b; Eberhard and McNice, 1982) and the nature of the plume's behavior in the lee of CCB. The lidar data helped the interpretation of data from surface samples of SF_6, which was released together with the oil fog. During some of the experimental hours, when a second elevated oil fogger released a plume well separated from the hill, the lidar performed scans through both plumes.

Real-time reports by the lidar crew of changes in the plume's position guided the experiment, especially in placement of the source. Hand-sketched maps (Eberhard 1981a; Lavery et al., 1982, pp. 41-42) were helpful for day-to-day planning as well as for establishing priorities for post-processing and analysis.

As processing was completed, the two-dimensional distributions of inferred tracer concentration in the individual scans were provided to ERT on digital magnetic tape and graphs (Eberhard, 1981a). The tapes also contained the location of the plume's center of mass, the instantaneous dispersion coefficients, and other useful information. Data from 37 experimental hours comprising 860 scans through the plume were eventually processed.

The lidar data proved valuable in several case studies (Strimaitis et al., 1983, pp. 59-265) of plume dispersion.

The hour-average horizontal dispersion σ_y of the lidar-observed oil fog plume was examined for distances (x) up to 1 km from the source. The dispersion followed (Strimaitis et al., 1983, pp. 36-38) a linear growth law

$$\sigma_y = \sigma_v \, x/U \ ,$$

where σ_v is the standard deviation of the lateral component of the wind, and U is the mean wind speed. Hanna (1983) used the lidar data to help show that mesoscale meandering of the wind, rather than smaller scale turbulence, usually dominates the hour-average horizontal dispersion in stable conditions. These authors also demonstrated that low winds and/or strong stability are necessary but not sufficient conditions for large σ_y.

Strimaitis et al. (1983, p. 39) also found that the measured average width of the instantaneous plume, given by σ_y'(inst) grew only very slowly with x. They failed to allow for the finite resolution of the lidar, given by σ_y(lidar), which artificially enlarged the true σ_y(inst) according to (Eberhard, 1981c)

$$[\sigma_y(\mathrm{inst})]^2 = [\sigma_y(\mathrm{inst})]^2 + [\sigma_y(\mathrm{lidar})]^2 \ .$$

However, this oversight did not invalidate their conclusion, except within the first couple of hundred meters or so downwind of the source.

The lidar data contributed most importantly to the development of a model for vertical dispersion in stable conditions. The earliest considerations of this problem, assuming only a square root growth law and using only lidar and meteorological data, are found in Lavery et al. (1982, pp. 122-126) and Eberhard and McNice (1982). Linear growth of the vertical dispersion coefficient σ_z near the source was added in Strimaitis et al. (1983, pp. 39-45). After more lidar data became available from post-processing, Venkatram et al. (1983) presented a more sophisticated analysis. Lavery et al. (1983, pp. 56-75) carried the development further, utilizing σ_z measurements derived from time-exposure photographs of the oil fog plume. This method was "calibrated" with lidar vertical profiles, which were fit by a Gaussian curve. The culminating work on this topic for CCB appears in Strimaitis et al. (1985b, pp. 36-45). Venkatram et al. (1984) reported the conclusions of their work based on CCB data. Venkatram's model for vertical dispersion is incorporated in the current version of the prototype Complex Terrain Diffusion Model (CTDM), which has been developed as part of the CTMD project. Later CTMD experiments, however, proved that vertical dispersion in stable conditions is still not adequately understood.

WPL also operated two acoustic sounders at SHIS#1 to characterize the structure of the boundary layer. One was sited by the lidar, and the other on the opposite side of CCB (Eberhard and McNice, 1982; Lavery et al., 1982, p. 25). Changes in the structure of the vertical profile of echo strength were frequently associated with dramatic changes in the wind and turbulence regime. The echoes from the two sounders were usually quite similar, but occasional significant differences indicated the presence of distinctive air masses in the vicinity of CCB. We also observed one case where a lee wave seemed to suppress the depth of the near-surface echo layer. We concluded that acoustic sounders could provide qualitative information useful to understanding turbulence in complex terrain. However, the instruments should have better vertical resolution and lower minimum range than possessed by those at CCB.

A frequency-modulated, continuous-wave, scanning radar measured the range-resolved wind parallel to its beam. The radar obtained vertical wind profiles using a conical scan about a vertical axis. It also acquired data on the structure of the wind flow in the vicinity of CCB. Its signal strength can provide information on the structure of the atmosphere in a manner analogous to the acoustic sounders. Unfortunately, a theft of the experimental logbook, real-time graphs, and part of the data processing computer hardware from the radar on the CCB site after the last experimental run prevented the use of these data (Eberhard, 1981b).

The involvement of WPL in SHIS#1 produced lidar data essential to the success of the CTMD project. The experience gained with the lidar and the other sensors figured strongly in the planning of the ensuing CTMD field studies.

3.2 Four Corners Complex Terrain Study

An aircraft operated by NOAA/Air Resources Laboratory and instrumented for air quality studies was a principal component of the proposal for the interagency agreement. However, the aircraft could not be used within the small spatial scales of CCB. A separate experiment on the plumes from the Four Corners and San Juan power plants in New Mexico was selected as an alternative. The project goals were to measure plume rise; observe the morning fumigation; investigate the behavior of the plumes in the vicinity of The Hogback ridge to the west and the Mesa Verde mountains farther to the north; and determine the suitability of the site for later experiments in the project.

Fifty flight hours with supporting surface measurements were completed between October 29 and November 10, 1980. Van Valin et al. (1982) discussed their results for the first three objectives. They found consistency between theory and the measured vertical oscillations of the plume in the lee wave of The Hogback. They also examined the enhanced dilution of large aerosols in the plume, presumably caused by wake effects, which increased the vertical diffusion and hence the deposition rate. Stearns et al. (1982) were also able to utilize data from the experiment in studying the effects of the optically dense Four Corners plume on radiative transfer. As reported by Eberhard (1981b), the dominance of easterly flow from the power plants toward The Hogback made this area attractive for further field studies of plume impaction on a ridge. However, flow toward the higher Mesa Verde mountains was rare and therefore unacceptable for future studies.

3.3 Stable Plume Experiment

As mentioned in Section 2, the Stable Plume Experiment (SPEX) successfully fulfilled its main objective of checking out the laser and data acquisition upgrades. The secondary objective was a lidar study of the dispersion of an elevated plume during stable conditions in the absence of complex terrain, although gently rolling terrain surrounds the BAO site. SPEX had the advantage of high quality wind, turbulence, and temperature profile measurements colocated with the tracer release, whereas the source at CCB was 1-3 km distant from the tall tower (Lavery et al., 1982). We delayed analysis of the SPEX data until 1986 in deference to the pressing need for processing of data from the collaborative experiments with ERT. Troxel and Eberhard (1986) describe SPEX and the conclusions of initial analysis.

The 300-m instrumented BAO tower was also the platform for elevated oil fog source. Release heights ranged from 37 to 266 m. A slower release rate than in our other experiments minimized the problem of attenuation of the probing light pulses by the plume (Eberhard et al., 1986b). Wind, turbulence, and temperature were measured at release height as well as at the regular tower levels (10, 22, 50, 100, 150 m, etc.). An acoustic sounder also operated during the experiment. The measurements were divided into an autumn and a spring phase. A tethered sonde obtained vertical profiles of the temperature and horizontal wind during the autumn phase, which helped to quantify instances of sharp transitions in the profile. A malfunction in the BAO data acquisition system unfortunately ruined most of the data from the spring phase. Lidar, tower, and meteorological conditions during nine periods totaling 245 min of data acquisition proved satisfactory for analysis.

Initial comparisons by Troxel and Eberhard (1986) found that the model of Venkatram et al. (1984) substantially underpredicted the SPEX measurements of σ_z. Draxler's (1976) empirical model had much less bias but considerably more scatter. We are examining the data and models more intensively in an attempt to determine the reasons for the discrepancies and intend to publish our conclusions.

3.4 Small Hill Impaction Study #2

The second major experiment in CTMD had objectives and philosophy similar to SHIS#1, except that the somewhat idealized terrain feature was a long ridge rather than a hill. A section of The Hogback just north of the San Juan River and some distance west of Farmington, New Mexico, was the site of Small Hill Impaction Study #2 (SHIS#2). With mesoscale drainage winds usually from the east, the windward side of the ridge rose to a height of about 75 m above the surrounding area at about a 15° incline, but sloped more gradually on the lee side. Terrain features in the fetch were considerably smaller than The Hogback, although not nearly so flat as at SHIS#1.

WPL operated a tethered sonde during the preliminary evaluative study (Lavery et al., 1983, pp. 112-117) at the site during June 6-11, 1982. C. W. King of WPL reported these data to ERT.

The lidar and several other WPL instruments participated in the main phase during October 5-29, 1982 (Lavery et al., 1983, pp. 123-140). The lidar maintained operational status for more than 90% of the experimental hours. The high visibility of the green pulses from the upgraded lidar system and coordination with on-site personnel in this remote area ensured their eye safety. From the lidar site, which was about 2.4 km away from the source and near the base of the ridge, the vertical scan planes intercepted the plume approximately parallel to the ridge's axis. The oil fog was released from part way up a 150-m tower or from a crane closer to the ridge. The lidar typically performed 60 scans per hour divided among five planes, with a scan in each plane once every 5 minutes. The scans had a strategy similar to that at SHIS#1, except that the plume in the lee of the ridge was out of the lidar's view. SF_6 was dispensed into the oil fog jet and sampled on the surface of the targeted terrain as at SHIS#1. A higher-performance oil fog generator at SHIS#2 caused more initial plume rise and plume growth than at CCB. Blocking of the flow by the ridge at times seemed also to lift the plume's trajectory. Scans over the ridge revealed the proximity of the plume to the ridge and the place where plume impaction occurred. Real-time reports of plume behavior kept the experiment director informed.

Post-processing of lidar data used the scan-by-scan interactive methods mentioned in Section 2. We reduced 3079 scans, which were spread over 84 experimental hours. The hourly average scans in the set number 304. Processed data were archived on digital magnetic tape, copies of which are available from the Atmospheric Sciences Research Laboratory of the EPA or from WPL. Interested researchers may also request photocopies of some of the graphical products from WPL. These graphs show the general behavior of the plume and are very helpful in screening the data set for particular types of events.

One exercise unique to SHIS#2 was normalization of the data by the oil release rate, which often changed during the course of the 1-hour averaging periods. A least-squares analysis involving the wind speed at plume height as a dilution factor determined the nonlinear relationship between the backscatter and oil release rate.

DiCristofaro et al. (1986, pp. 117-136) incorporated the lidar data in studies of case hours with the highest tracer concentrations at the surface. The fogger's distortions of early plume growth, combined with the short distance between the source and the point where the flow "felt" the presence of the ridge, have prevented any refinement of the σ_z model with SHIS#2 lidar data.

Strimaitis et al. (1985a) investigated methods to model the stand-off distance of the oil fog plume as it passed over the crest of the ridge.

DiCristofaro et al. (1986, pp. 58-75) contains a slightly expanded discussion of the same topic. The critical height H_c is the height far upwind of the ridge above which the air flow has sufficient kinetic energy to overcome the potential energy of the stable profile and pass over the ridge. Their comparisons indicated that the streamline deflection near the crest can be explained fairly well by assuming a psuedo-surface at H_c and calculating the neutral potential flow over the part of the ridge extending above H_c. (This treatment succeeded much better than a potential flow calculation using the actual surface and ridge height.) A perturbation analysis then showed some improvement when the stratification above H_c was included. Incorporation of wind shear gave little additional improvement.

Lidar ranging on experimental landmarks revealed an error in the conventional site survey and showed the way to correcting the error (Eberhard and Troxel, 1983; Greene, 1985, p. 3-3).

WPL operated a Doppler acoustic sounder at a site about 1.8 km east (and usually upwind) of the tracer sampling area on The Hogback. This instrument measured the vertical profile of the horizontal wind in the approach flow nominally between 50 and 250 m above the surface at 20-m intervals. This particular bistatic unit scanned the transmitter beam along the receiver's vertically pointed receiver. Neff (1983) found evidence for distortion of the profile below 60 m when refraction by a strong temperature gradient and/or a low-level wind jet bent the transmitter beam. He recommended that a monostatic version would eliminate this problem. Problematic data were removed before Neff shipped the data sets to ERT. The profiles were also provided on digital magnetic tape. Neff (1983) gave an example wind profile from the Doppler acoustic sounder.

A tethered sonde obtained vertical profiles of temperature, humidity, and horizontal wind to about 300 m height near the upwind base of the ridge during the first part of the experiment. The wind often blew the balloon far enough over the crest, which sometimes confused the interpretation of the wind profile. We therefore moved the sonde to near the Doppler acoustic sounder during the last part of SHIS#2. C. W. King supplied the edited data to ERT on magnetic tape as well as printed tabulations and graphs. These data are also available from EPA's Atmospheric Sciences Research Laboratory (Truppi, 1985).

WPL operated an acoustic sounder at the upwind base of the ridge near the tethersonde's first site, which was also near a 30-m instrumented tower. A second sounder functioned near the 150-m tower, from which photographs of the facsimile records of the echo structure were later supplied to ERT. Whenever noise from the oil fogger interfered with this instrument, data from the other sounder were substituted. Neff (1983) described typical echo structures and the implied dynamics of the boundary layer during SHIS#2.

Sonic anemometers, which measure the three components of wind and turbulence, were placed at the 5 and 40 m levels of the 150 m tower (Neff, 1983). The addition of a high speed temperature sensor made possible the measurement of vertical heat flux. The temperature sensor proved too fragile for the rigors of installation at the 40-m level, so ERT supplied a more rugged but less sensitive thermistor. WPL's computer data acquisition system, which was developed as part of CTMD, sent 20-min averages of means, variances, and covariances of the sonic and fast temperature sensors to a printer in the command center. After undergoing post-processing and editing, these data were supplied to ERT on digital magnetic tape as documented by Eberhard (1985b).

Because of their high speed response, the sonic anemometers measured the vertical turbulence much more accurately than the props, which were used at all instrument levels on the tower. The data from the sonic anemometers therefore played a major role in quality assurance and calibration of the props (Strimaitis et al., 1985b, pp. 77-84; DiCristofaro et al., 1986, pp. 36-58; and Greene, 1985, pp.4-35 to 4-58). The modeler's data archive directly incorporated (Strimaitis et al., 1985, p. 98) measurements of vertical turbulence from the sonic anemometers.

Neff (1983) demonstrated that cold air advection along slopes in complex terrain often contributes significantly to heat flux measurements at low frequencies. One must remove this portion before interpreting the data as vertical heat transport caused by turbulence.

Optical crosswind anemometers were another type of device that WPL operated at SHIS#2. Truppi (1985) documented the data that have been archived with EPA on digital magnetic tape. An optical beam between a transmitter and receiver sensed the motion of scintillation patterns to obtain the path-averaged component of the horizontal wind perpendicular to the beam. The device is sensitive even to near-zero average winds. Each of these three anemometers had a path about 500 m long and typically 8 m above the surface in the same area as the array of gas samplers (Fritz, 1983). One path was located near the windward base of the ridge, the second near the crest, and the third slightly down the lee slope. The path along the crest typically showed the strongest winds, and winds at the windward path were similar. The path at the base of the ridge measured light winds, often downslope in opposite direction of the main flow above. Fritz (1983, 1984) discussed some of these results.

Scientists at WPL contributed Appendix D of the experiment's quality assurance report (Greene, 1985).

3.5 Preliminary Full Scale Plume Study

EPA tentatively selected the Tracy Power Plant on the Truckee River east of Reno, Nevada, as the site for the culminating field experiment of CTMD. EPA and the Electric Power Research Institute cosponsored a preliminary experiment (Strimaitis et al., 1985b, pp. 153-164) that verified the suitability of the region for the main Full Scale Plume Study (FSPS). The plant is situated within a bowl formed by the surrounding mountains. The drainage flow typically carries the plume in the general downriver direction. About 4 km from the plant the river makes a cut in an S-shape through higher terrain. The plume often impacted the mountains on either side of the S-curve. The preliminary FSPS, which took place November 7-20, 1983, was large enough in scope to produce a considerable data set of its own. It included meteorological measurements by instrumented towers, tethered sondes, acoustic sounders, and optical anemometers. Fifty-three syringe samplers obtained the concentrations of SF_6 tracer gas in the region; the plant's stack was the source location. Since the plume of this gas-fired plant was invisible to the eye, an oil fog generator injected an ample quantity of aerosols into the stack's ductwork for flow visualization. The oil fog was observed by photography and by an airborne lidar.

WPL operated a Doppler acoustic sounder within a few hundred meters of the stack to obtain vertical profiles of the horizontal wind near the tracer source. Neff shared the results with ERT in tabulated and graphical form as well as on digital magnetic tape. A tethered sonde performed measurements near the river as it entered the S-curve. These data were reported to ERT by King of WPL. An acoustic sounder also operated beside the tethered sonde. The echo profiles from the two acoustic sounders were used for on-site observation and evaluation, but were not archived with ERT or EPA.

WPL also operated a pair of optical anemometers in a bowl separate from that containing the Tracy plant. The presence of this bowl could influence the behavior of the Tracy plume, because air draining from mountains around the bowl exited primarily through an opening near the beginning of the S-curve. The horizontal paths of the two optical anemometers, which averaged about 12 m above the surface, crossed in approximately orthogonal directions. This was the first time crosswind optical anemometers were operated in this configuration, which allowed calculation of the area-average wind direction and speed of the flow in the bowl. The optical anemometers in this setting had the advantage over conventional point measurements of being insensitive to perturbations of the flow by local small-scale topography. Eberhard (1984) provided tabulations of the reduced data to ERT.

Data from all the WPL instruments contributed to case studies (Strimaitis et al., 1985b, pp. 167-219) of the preliminary FSPS results.

3.6 Full Scale Plume Study (Main Phase)

The main FSPS (DiCristofaro et al., 1986, pp. 10-28) took place August 6-27, 1984, at the Tracy Power Plant. The topography and flow structures were more complicated than at CCB or The Hogback. This experiment provided data for testing numerical models in a realistic setting. Compared with the SHIS projects, the height of the plume was more typical of those actually created by industry. The plant generated power only during the last few days of the experiment, but the stack blower operated most of the rest of the time. SF_6 and oil fog were released simultaneously from the stack. Most experimental runs of tracer measurements commenced after the onset of deep, westerly drainage flow and continued through the diurnal flow reversal after sunrise. The runs typically lasted 10 h.

WPL's lidar normally performed 60 scans per hour divided among five planes as at SHIS#2. The lidar was eye-safe where the beam struck terrain at longer ranges. The scan remained above closer terrain, except in remote areas where entry was allowed only by coordination with experiment participants. The lidar had an adequate view in the vicinity of the stack to measure plume rise and "initial" plume dimensions in the one or two scan planes closest to the source. During westerly flow, the lidar also observed the plume as it approached and interacted with mountains near the S-curve. Interference of aerosols from a diatomaceous earth processing plant at the entrance to the S-curve prevented the lidar from successfully using a scan plane that peered part way into the river cut. On those occasions when the plume was carried up the valley toward the west, the lidar measured plume rise and growth, but an intervening hill blocked the view of plume interaction with terrain. The lidar crew made real-time reports of plume behavior as during the SHIS experiments.

The lidar assisted in surveying positions of key experimental landmarks (Eberhard, 1985a). The system performed satisfactorily for 95% of the experimental runs when oil fog tracer was available.

We reduced the lidar data with the same software tools that had been applied to SHIS#2. Troxel et al. (1986) described in detail the lidar processing for FSPS, which produced a data set with 4509 scans that were divided among 84 experimental hours. Graphs, tables, and data on magnetic tape were periodically shipped to ERT. An archive on digital magnetic tape is available from EPA's Atmospheric Sciences Research Laboratory or WPL. The archive includes two-dimensional distributions of the tracer in the hourly-averaged cross sections; centroid location of the individual (5-min interval) and hour-averaged scans relative to the lidar, the stack top, and Universal Mercator Projection coordinates; and the size of the plume in the individual and hour-averaged scans. The case study in DiCristofaro et al. (1986, pp. 136-153) shows several of the routine graphical displays produced during WPL's processing. WPL can supply researchers with copies of graphs for specific periods.

Paine et al. (1986) found that wind speed and temperature data at a point midway between the stack top and final plume height predicted the lidar-observed plume rise better than did the meteorological data at stack top only. Since the height of the plume relative to H_c determines if and where plume impaction will occur, the lidar data are valuable in research with FSPS data (e.g., DiCristofaro and Egan, 1986).

DiCristofaro et al. (1986, pp. 96-107) investigated vertical dispersion for 14 of the more stable cases at FSPS. The plume's growth during the initial buoyant rise dominated σ_z for the first few kilometers downwind of the source. The CTDM and other models overpredicted the additional plume growth beyond the lidar scan plane nearest the source. High priority will be given in CTMD to further analysis of σz (DiCristofaro et al., 1986, p. 233).

Sonic anemometers were installed at the 10-, 100-, and 150-m levels of the 150-m instrumented tower, which was located about 1.5 km downriver from the Tracy plant. WPL also provided a data acquisition system housed in a trailer near the base of the tower. As at The Hogback, data were reduced in real time and displayed in the command center. More careful processing and quality assurance after the experiment yielded an organized data set of means, variances, and covariances on digital magnetic tape, which was sent to ERT. We anticipate that these data will be valuable for understanding the growth and movement of the plume caused by turbulence and gravity waves. For instance, a researcher at EPA has received the wind measurements at 10 s^{-1} sampling rate for one of the experimental nights, for in-depth analysis.

WPL operated one Doppler acoustic sounder near the Tracy plant and another near the beginning of the S-curve. The profiles of wind were obtained from 50 m up to as high as 400 m above the surface at 25-m intervals. Static electricity in the dry climate of FSPS caused frequent crashes of the computer data acquisition systems. A significant fraction of the data were lost, more than half at the site near the S-curve. However, many valuable data were retrieved, processed, and provided to ERT by Neff as printed tabulations and on digital magnetic tape.

An acoustic sounder in the vicinity of the 150-m tower presented the echo structure on a real-time facsimile display in the nearby command center for experimental guidance. The Doppler acoustic sounders each produced a facsimile record also. Neff (1985) annotated photocopies of the record from the sounder near the plant to show the existence or location of the skin layer, elevated layers, waves, intrusions of new air masses, etc. Lavery et al. (1986) incorporated this information in their summary of the air pollution meteorology extant during FSPS.

WPL also operated a tethered sonde in the vicinity of the 150-m tower. During some experimental hours the sonde profiled the horizontal wind, temperature, and humidity. During the other hours the sonde was held at the approximate height of the oil fog plume after its buoyant rise to measure the wind at effective plume height. King provided the data to ERT on computer-generated graphs and tables and also on digital magnetic tape.

Research on the FSPS data set is in progress. One activity at WPL involves separation of the contributions to the variance of vertical velocity by turbulence versus waves. Spectral analysis of sonic anemometer data by Neff (1986) for one night revealed significant contributions by waves to the variance at frequencies ranging from a few per hour down to the inertial subrange, which was characteristically confined to frequencies higher than 0.1 Hz. Both wave motion and turbulence contributed to the variance at frequencies between the inertial subrange and the buoyancy frequency. The dominant mode at frequencies lower than the buoyancy frequency was consistent with the natural oscillation frequency in the Tracy basin. Further study of FSPS data in this respect is anticipated.

Task leaders at WPL have submitted individual quality assurance reports for FSPS that should become part of the master report. More results from FSPS should be forthcoming, including a final report by ERT on CTMD, that will rely at least partly on WPL measurements.

4. RELATED LIDAR ACTIVITIES

WPL's plume mapping lidar has participated in two noteworthy plume dispersion experiments that were not part of CTMD.

The first such experiment was the drainage flow study in autumn 1980 in the Anderson Creek valley of The Geysers area near Middletown, California. This study was part of the Department of Energy's Atmospheric Studies in Complex Terrain program. Eye-safe operation of the lidar at the ultraviolet wavelength (Eberhard, 1983) was essential, because the research area was populated with ranchers and geothermal energy workers. Eberhard et al. (1981) showed the layout for the lidar and the oil fog generator. Gudiksen et al. (1984) described all the tracers in the experiment and discussed some of the results. The lidar revealed a patchiness in the oil fog distribution that was not observable by the methodology of the other tracers. A perfluorocarbon tracer gas was released almost simultaneously with the oil fog. However, vertical profiles of the gas sometimes differed considerably from nearby vertical profiles of the oil fog. The cause is not clear, but the possibilities point out the importance of strong gradients in the air pollution meteorology of very complex terrain.

The second project was Convective Dispersion Observed by Remote Sensors (CONDORS) at the BAO, which is surrounded by gently rolling terrain. Moninger et al. (1983) and Eberhard and Lavery (1984) gave some preliminary results from the first phase in 1982, and Eberhard et al. (1985) exhibited additional early results from the 1983 main phase. A full description of the project and data tabulations are given by Kaimal (1986). Briggs et al. (1986) give some results of more in-depth analysis. The BAO's 300-m instrumented tower provided wind and turbulence data of high quality. CONDORS produced a comprehensive set of vertical profiles of tracers, which had been released from the surface or elevated positions into the highly convective boundary layer near midday. The lidar's fast scan capability was crucial to the success of the experiment. The scans did not extend all the way to the surface, so eye safety was not an issue. In a quantititive comparison, inferred oil fog concentrations near the surface agreed well with concentrations of SF_6 that had been released simultaneously with the oil fog (Eberhard et al., 1985; Kaimal et al., 1986). We were also able to confirm the semi-conservative nature of the oil fog tracer, which experiences a gradual loss with residence time in the air. The lidar capabilities developed by WPL under CTMD made the important CONDORS experiment possible.

5. SUMMARY

Instrument systems from NOAA/WPL participated in joint and individual experiments as part of EPA's CTMD project. The goal of the project is development of a dispersion model valid in complex terrain with emphasis on impaction of elevated plumes on high terrain during stable conditions. A combination of remote and other specialized sensors enabled WPL to gather data that were crucial to progress in model development.

The first joint experiment, which was SHIS#1 at Cinder Cone Butte, included a plume-mapping lidar, two acoustic sounders, and a scanning clear-air radar with Doppler capability for wind measurements. At the second joint experiment, SHIS#2 at The Hogback, WPL operated an upgraded version of the lidar, a Doppler sodar, two other acoustic sounders for echo intensity alone, a tethered sonde, two sonic anemometers as part of the instrumentation on a 150-m tower, and three cross-wind optical anemometers. WPL assisted in the preliminary FSPS, which was actually a rather large experiment in itself, with a Doppler sodar, an acoustic sounder, a tethered sonde, and a pair of optical anemometers. The last and largest experiment of the project, the main phase of FSPS, involved the lidar, two Doppler sodars, an acoustic sounder, a tethered sonde, and three sonic anemometer units. On-site data from these instruments helped guide the conduct of the experiments and screening of the cases for intensive study. Processed data were later provided to ERT for quantitative analysis.

An instrumented aircraft of the NOAA Air Resources Laboratory performed a separate study of plumes from the Four Corners and San Juan power plants. The Hogback, a long ridge in the vicinity, was also chosen as the site of a later, more intensive experiment. The other individual project, which was principally a successful test of the upgraded lidar system, also produced a useful data set on dispersion of an elevated plume during inversion conditions.

The lidar measured the two-dimensional concentration patterns of an oil fog tracer in discrete cross sections through the plume. These data revealed a variety of information, such as the plume rise, vertical and horizontal dispersion, and the diversion of the flow by terrain obstacles. A major improvement to increase the lidar's scan rate was performed as part of the project. Interactive software was developed that allowed extraction of a voluminous amount of dependable concentration data in spite of the presence of several contaminating factors in the signal. These new capabilities allowed the lidar to participate effectively in other plume dispersion experiments.

Sonic anemometers provided accurate turbulence data. Their contribution in the vertical is the most important, because vane and propellor devices respond marginally to the high frequencies that are important in stable conditions.

Acoustic sounders indicated the structure of the surface layer and elevated inversions by the strength of the scattered echo. Doppler versions of this instrument were able to measure the vertical profile of the horizontal wind.

A sonde flown beneath a tethered balloon inflated with helium obtained vertical profiles or elevated time series of the horizontal wind, temperature, and humidity.

Crosswind optical anemometers were able to measure path-integrated flow normal to an optical beam between a transmitter and separate receiver. Not only can they measure remotely, but they function well to very slow speeds where mechanical anemometers become inaccurate.

The technology of these devices fortunately matured in time to meet the needs of the ambitious CTMD project. The two main purposes for WPL's participation in CTMD were successfully met. We were able to evaluate and demonstrate the capabilities of these devices for studying atmospheric dispersion. We were also able to collect data sets during CTMD's experiments that contributed to understanding of the dispersion caused by the flow and turbulence in complex terrain.

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