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Project Summary

Development of Measurement Methodology for Evaluating Fugitive Particulate Emissions

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An experimental study was conducted to demonstrate a measurement methodology for evaluating fugitive particulate emissions. The program focused on the application of the lidar (laser radar) technique under field conditions but in circumstances that simplified and controlled the variables of the general problem.

The lidar was used to make elevation scans perpendicular to an aerosol plume generated by controlled release of particulate material into the atmosphere. The lidar backscatter signatures were processed in terms of cross-plume integrated backscatter, and these values were related to independently measured particulate emission rates. A very high correlation was obtained between time-averaged lidar observations and emission rates (correlation coefficients of 0.9 or better in most runs), with substantially less correlation for individual lidar observations. Relatively high correlations were also obtained between smoke-reader data on downwind plume opacity and smoke emission rate as well as lidar backscatter. For dense smoke, attenuation of the lidar energy was shown to be of importance in interpreting data in terms of smoke concentration.

Finally, the lidar was used at the site of an actual fugitive particulate source to demonstrate that appropriate data can be collected for measuring source emission rates.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The total source strength of pollution emitted by industrial plants is the aggregate of all diffuse and minor specific emissions as well as major identifiable point sources. Therefore, for many plants, measurement of individual emissions from a multiplicity of sources is neither economical nor practical. The only feasible approach is to measure, as accurately as possible, the concentration throughout a cross section of the downwind plume of the combined fugitive emissions, to integrate these, and, from a measurement of the integrated wind velocity through the plume of the cross-section, to calculate the pollutant mass flow.

The problems of accomplishing such measurements with existing technology are many. Specifically, with *in-situ* samples it is virtually impossible to characterize adequately the concentration of particles throughout the total cross section of the plume, to relate any measurements made to the plume's total envelope, or to determine its extent. This is especially the case above the surface, because of the extended and variable nature of the multiple sources of fugitive emissions.

Lidar observation fulfills, as no other method does, the requirement for delineating the spatial distribution of elevated particulate pollution plumes and for readily distinguishing between pollution background and pollution from the source being studied. Although there are limitations and difficulties in using lidar backscatter measurements for determining absolute particulate concentrations, it is possible to evaluate, with useful accuracy, the near-instantaneous distribution of particulate material within a selected cross section or envelope. It is thus possible to obtain a series of such cross sections in time and, from a measurement of mean wind velocity and information on the backscatter-to-mass-concentration ratio, to derive an estimate of source emission rate.

In the present study, three experimental field programs were conducted to demonstrate a lidar methodology for measuring fugitive particulate emissions. The first two field programs used controlled release of various types of particulate material to simulate emissions from fugitive sources. A lidar system was used to make elevation scans perpendicular to the transport direction of the aerosol plume about 500 m downwind from the source. The lidar backscatter signatures for each elevation scan were processed for values of cross-plume integrated backscatter, and these values were related to independently measured particulate emission rates. In the second field test, a trained smoke inspector made downwind plume-opacity readings in addition to the lidar observations. The third field program was conducted to demonstrate use of the lidar technique at the site of an actual fugitive emission source.

Results of this study showed that downwind measurements of lidar cross-plume integrated backscatter and smoke-reader plume opacity generally increase linearly with particulate emission rate. Relatively high correlation coefficients between these measured quantities demonstrate that lidar and smoke reader provide two possible methods for evaluating fugitive particulate emissions.

Procedure

A series of field experiments was designed to demonstrate the methodology by making lidar measurements of an aerosol plume generated by continuous release of particulate material of known properties into the atmosphere at known rates. The lidar system used was SRI International's Mark IX, which is van-mounted complete with data-processing and power-generating capabilities. Figure 1 is an example of an intensity-modulated video display depicting cross-plume aerosol structure observed by scanning the lidar in elevation. Computer-generated vertical concentration profiles are plotted on the cross section for locations indicated by the cursor marks drawn above the plume return. Similarly, the backscattered data can be spatially integrated to determine a relative cross-plume density.

The Mark IX lidar was used to make cross-plume observations downwind from controlled emission sources with known particulate properties, as shown by the example presented in Figure 1. The lidar typically observed the plume from a distance of about 300 to 500 m, about 200 to 500 m downwind from the source. On some experimental data runs, the trained smoke inspector made plume-opacity readings near the emission source; on other runs he made readings at downwind distances corresponding to the lidar observations.

Three methods of aerosol generation were used. An aerosol generator was constructed for releasing fine silica powder in the atmosphere at 1-m and 10-m heights. The powder emission rate was controlled by a grooved-disk feeder.

A second method of aerosol generation used a smoke generator operated by the State of California Air Resources Board for certifying smoke inspectors. Both white smoke (produced by vaporization and condensation of diesel fuel) and black smoke (produced by incomplete combustion of toluene) could be emitted through a 10-m modified stack. The white smoke was found to evaporate downwind from the source; therefore, only black smoke was used in the experiments. The emission rate was controlled by the fuel combustion rate, and smoke quantity was evaluated with an in-stack white-light transmissometer calibrated in terms of mass emission.

The third method of smoke generation consisted of igniting zinc chloride smoke pots and candles. The mass emission rate was determined by experimentally evaluating the emission from a single pot and candle and multiplying by the number of pots or candles (1, 2, 4, or 8) ignited simultaneously.

Results and Discussion

The experimental results of this study show linear relationships of relatively high correlation among the quantities of downwind lidar cross-plume backscatter, smoke-reader plume opacity, and particulate emission rates. This is illus-

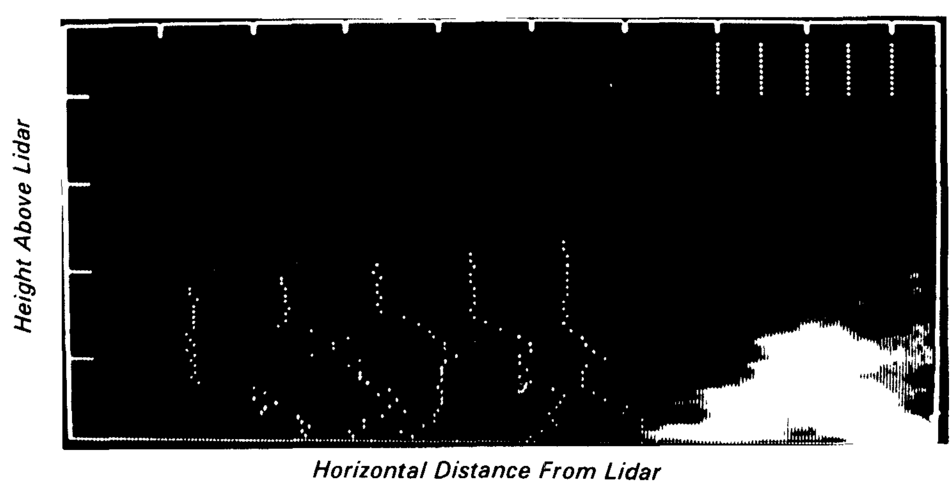


Figure 1. *Example of computer-generated profiles of vertical plume density. Lidar is located at lower left corner. The height and distance scale is 75 m/div. Vertical concentrations of the plume (relative to clear air, with a scale of 10 dB/div) are plotted at the lower left and the horizontal position associated with each profile is plotted in the upper right.*

rated by the example presented in Figure 2 for data collected during a smoke candle experiment. This example and other data presented in the final report demonstrate the feasibility of using either lidar or smoke inspectors for estimating particulate emission from fugitive sources.

Relatively large scatter of data occurred, probably caused by downwind aerosol density fluctuations introduced by turbulent transport. Linear correlation coefficients squared for all data points (R_i^2) collected during an experimental run typically ranged from 0.6 to 0.9. By averaging data from three or four lidar scans at each smoke concentration (requiring a 5- to 10-minute period), the correlation coefficients squared (R_m^2) typically were greater than 0.9. Therefore, the data clearly show that time-averaged measurements of the downwind plume are required.

For high-density smoke generated by igniting smoke pots, significant attenuation of the laser energy was evident. A factor-of-two increase in the emission rate resulted in substantially less than a factor-of-two increase in the cross-plume integrated lidar backscatter. Experiments with lower-density smoke provided the expected one-to-one correspondence between lidar response and smoke emission rate.

Plume opacities derived from the lidar data by analyzing the clear-air returns on the far side of the plume returns were substantially less than those estimated by the smoke reader. Correction applied because of the longer wavelength lidar and submicrometer smoke particles explained only a part of the difference between lidar and smoke-reader observations.

A field program was conducted to demonstrate the use of the lidar system at an actual fugitive emissions source. The lidar was used successfully to make downwind vertical scans across the particulate plume generated by the Permanente Cement Plant located in Cupertino, California. The data were collected in the same way as the test smokes and therefore could have been processed in the same way as the test data to estimate plant particulate emission rates.

Conclusions

The major conclusions of this study are:

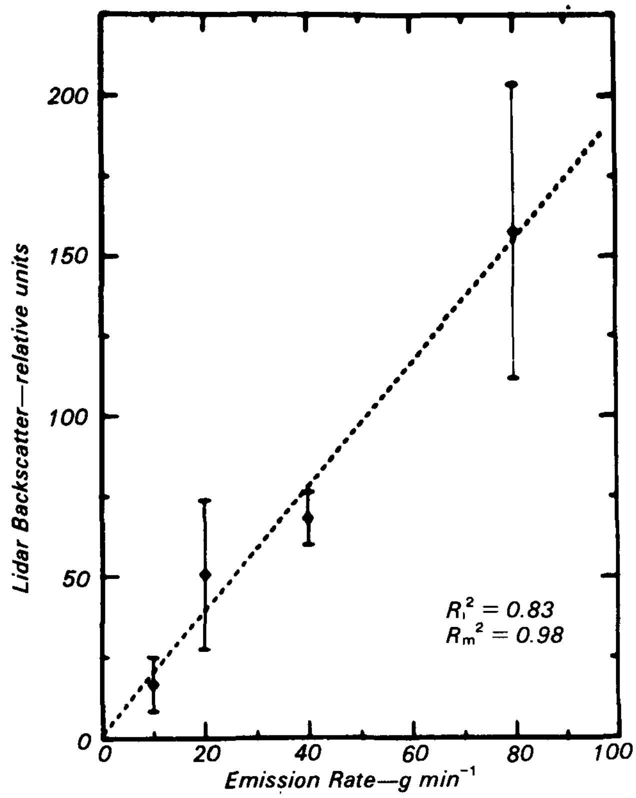
- Cross-plume integrated backscatter evaluated from data collected by scanning a lidar system across a downwind smoke plume behaved predictably with variations in particulate emission rate.
- Correlations between downwind lidar observations and source emission rates were greatly increased by averaging data from multiple lidar observations made at each emission rate (three or four lidar scans requiring 5 to 10 minutes).
- For low-density plumes, the lidar responded linearly in a one-to-one ratio with changes in particulate emission rate. Linear correlation coefficients greater than 0.9 were obtained in most cases.
- For higher-density plumes, the lidar signal increased with increasing particulate emission rate, but at less than a one-to-one ratio because of extinction processes.
- Correlations between downwind lidar observations and particulate emission rates were only slightly improved when corrections for wind speed variations (measured at the lidar site) were applied.
- Testing of lidar methodology was best accomplished using commercially available smoke candles. The quantity of smoke was controlled by the number of units ignited.
- Downwind plume opacities evaluated by a trained Method-9 observer were highly correlated with particulate emission rate and with the lidar cross-plume integrated backscatter.
- A mobile lidar system can successfully make appropriate cross-plume observations at actual fugitive particulate emission sources.

Recommendations

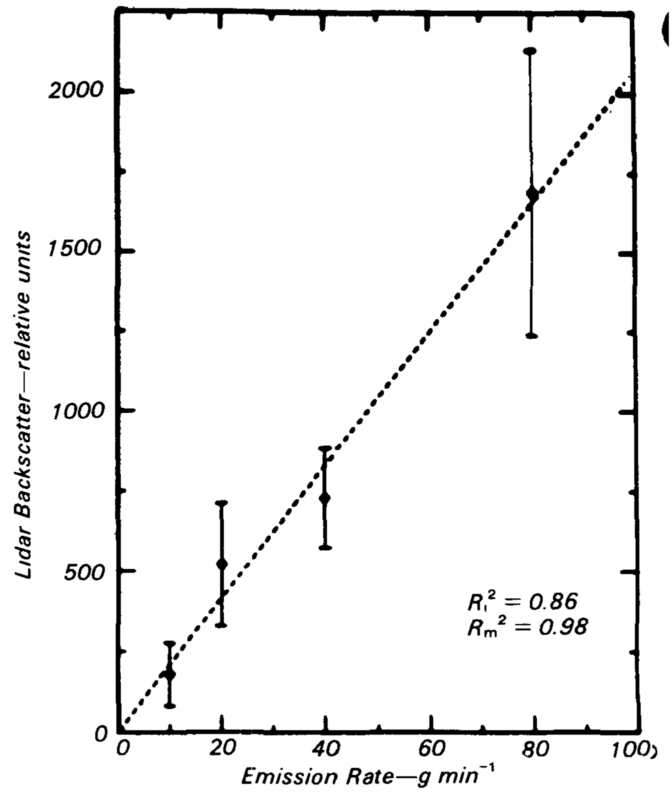
This study demonstrated a methodology, using the lidar technique for measuring fugitive particulate emissions. Several additional studies suggested to further develop and demonstrate the lidar technique for this purpose are discussed below:

- In-Situ *Measurement of Backscatter-to-Mass-Concentration Ratio*—The study showed that the cross-plume integrated backscatter evaluated by scanning a lidar system across an aerosol plume responds predictably with particulate emission rate. However, measurement of the absolute emission rate requires calibration of the lidar backscatter in terms of aerosol concentration. An *in-situ* measurement of the backscatter-to-mass-concentration ratio would provide the needed calibration. In addition, the measurement of the variability of this ratio for different types of particles would provide an estimate of the accuracy of lidar measurement for the case of particle characteristics changing in the vertical. Therefore, an instrument that measures absolute values of backscatter-to-mass-concentration should be developed.
- *Airborne Lidar Measurement of Particulate Emissions from Large-Area Sources*—Many fugitive emission sources, including coal mining, oil refining, and cement plant operations, generate a particulate plume with a large horizontal and vertical extent. From these sources, the pollution plume is more readily observed with an airborne lidar than with a surface-based system. A downward-pointing lidar could be flown along a path that encompasses the plant site to observe upwind and downwind particulate flow. Observations made in complex terrains would be greatly simplified as compared with those using a surface-based lidar. A two-wavelength airborne lidar system has recently been demonstrated.* Backscatter data at two wavelengths may provide the necessary information to estimate absolute mass concentration of observed aerosols. An airborne lidar system should be considered for measurement of particulate fugitive emissions.

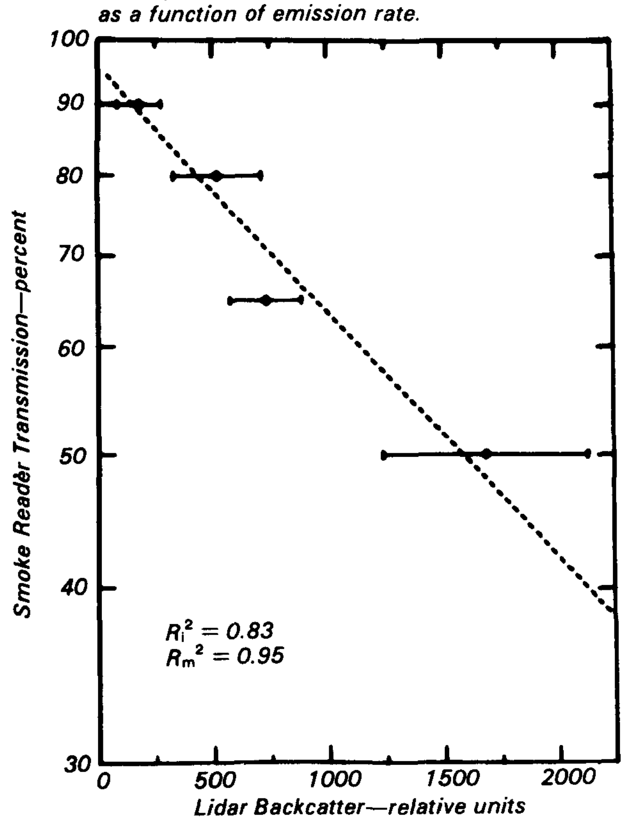
*Uthe, E. E., N. B. Nielsen, and W. Jimison, "Airborne Lidar Plume and Haze Analyzer (ALPHA-1)," *Bull. Am. Met. Soc.*, **61**:1035-1043, 1980



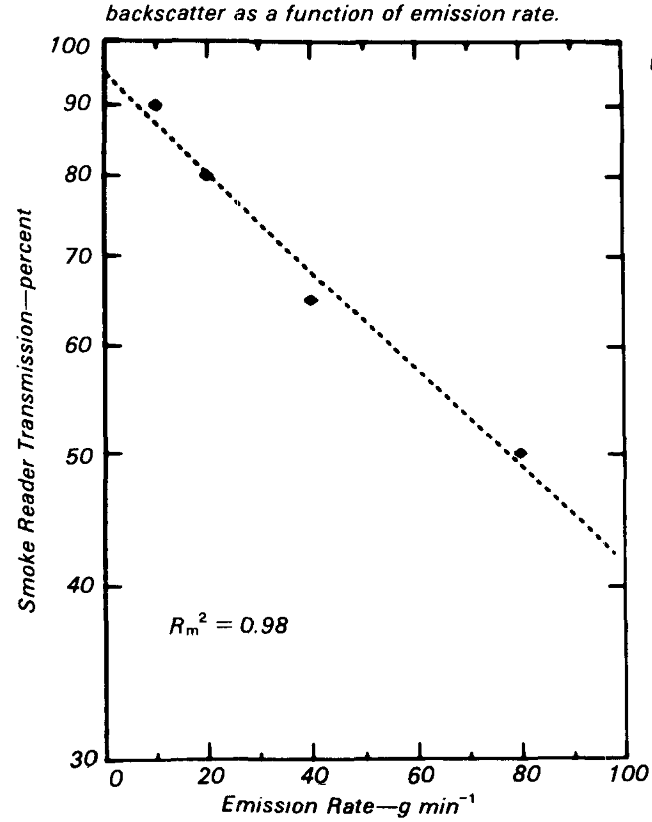
(a) Cross-plume integrated backscatter as a function of emission rate.



(b) Wind-corrected cross-plume integrated backscatter as a function of emission rate.



(c) Smoke reader transmission as a function of integrated backscatter.



(d) Smoke reader transmission as a function of emission rate.

Figure 2. *Lidar, emission, and smoke reader data for smoke candles (15 August 1979, 1923-1949 PDT). 5 m release height, 12 lidar cross-sections.*

- *Choice of Lidar Wavelength or Wavelengths*—Successful use of the lidar technique for remote measurement of particulate concentrations require knowledge of the relation between aerosol optical and physical parameters. Because fugitive emissions frequently are comprised of emissions from several source types and the percentage of particulate from each type may vary, the particle characteristics (size, shape, and composition) may also vary in both space and time. The backscatter-to-concentration ratio is dependent on these particle characteristics and, therefore, a fugitive-emissions lidar system must be designed to be insensitive to changes in particle characteristics. Experiments should be conducted to establish the proper wavelengths for minimizing the effect of particle characteristics on the backscatter-to-concentration ratio.

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***William D. Conner** is the EPA Project Officer (see below).*
The complete report, entitled "Development of Measurement Methodology for Evaluating Fugitive Particulate Emissions," (Order No. PB 81-196 594; Cost: $8.00, subject to change) will be available only from:
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