AIR POLLUTION MONITORING BY COMPUTED TOMOGRAPHY

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ABSTRACT

This paper discusses the simulation of a tomographic system that would be used for air pollution measurements over the range of 1 to 10 km. Results are presented that establish the feasibility of such a system from a signal-to-noise standpoint. Pixel signal-to-noise data and phantom reconstructions are presented.

INTRODUCTION

In this paper, we describe the application of computed tomography to the problem of regional air pollution monitoring. First, we briefly discuss the current laser radar measurement capability so that the motivation for a tomographic system is clarified. We then describe a tomographic system for making two dimensional maps of pollutant concentration from ranges up to 10 km. In the following sections the results of numerical simulations of tomographic measurements with a CO2 laser source operating at 10.6 microns are presented so that the feasibility of the technique may be assessed. Estimates of the system signal-to-noise, sensitivity and range are given.

LASER RADAR

Before 1970, regional air pollution was confined to local monitoring stations which took air samples and performed chemical analysis on them. Spatial resolution was poor due to the cost of installing many monitoring stations to cover metropolitan areas. In addition, temporal resolution was poor as the chemical methods employed require integration times on the order of hours. As a result of these problems, researchers began to investigate the use of laser radars or LIDAR as a means of supplanting chemical monitoring. The two most commonly employed methods utilize molecular absorption by the pollutant of interest as a measure of pollutant concentration. In the long path absorption method, a pulse transmitted from the laser travels through the pollutant cloud, is reflected from a tree or hill serving as a retroreflector, travels back through the cloud, then is collected by a receiving telescope and finally focused onto a detector. In the differential absorption or DIAL method, there is no remote retroreflector. Scattering from the particulates in the atmosphere serves as a distributed retroreflector, thus leading to depth resolved absorption measurement capability. Both long path absorption and DIAL may be described by a range equation derived from conservation of energy

\[ P_r = \frac{KC}{R^2} P_t \exp \left[ -2 \int_0^R \alpha(t) \, dt \right] \]  

(1)

Where \( P_r \) is the received power, \( P_t \) is the transmitted power, \( A \) is the receiving mirror area, \( R \) is the range, \( K \) is a term representing the optical losses in the system, \( \alpha \) is a loss term including both scattering and absorption. In the case of long path absorption, the \( C \) term represents the reflectivity of the retroreflector in the receiving telescope direction while in the case of DIAL this term represents the effective reflectivity of all of the particles contributing return at a given time. In this latter case, the reflectivity is equal to half of the spatial pulse width as this is the amount of path length contributing to the signal at any given time. It is important to note that this feature of the scattering in the DIAL case makes it possible to use DIAL for range resolved measurements. Such a measurement is not possible from a long path system because the retroreflector is not distributed along the propagation path and hence the long path measurement yields the path average of the concentration.

Because scattering from particles is orders of magnitude weaker than from a retroreflector, the advantage of range resolved measurements comes at a high price in transmitted energy. Moreover, the required energy increases with wavelength of
operation due to the $1/\lambda^4$ variation in Rayleigh scattering from the gaseous constituents of the atmosphere.

The remaining Mie scattering is relatively weak, necessitating the use of high energy tunable sources. The problem is increased because of less detector sensitivity in the infrared and because absorption lines of the species of interest occur in just this region. These factors, coupled with power limitations on present day tunable laser sources, have greatly restricted the range and resolution capabilities of DIAL LIDARS. An excellent review of the current state of the subject may be found in ref. 2. What is needed is a measurement method that can give spatial resolution without depending on weak scattering and the resultant high energy transmitter source.

LASER TOMOGRAPHIC MONITORING SYSTEM

It then remains to be seen how tomography might be applied to this problem. One proposed solution was recently given by Byer and Shepp. This measurement system is shown schematically below in Fig. 1.

A central laser illuminates in sequence $M_i$ mirrors placed on elevated supports around the area to be monitored. Each of these mirrors is designed to spread the incident radiation into a fan beam. The fan beam illuminates a series of $D_j$ detectors, which for convenience may also be mounted on the mirror support structures. The different angles for a tomographic scan are achieved by rotating the central laser beam. Basically what has been done is to replace the requirement for source rotation by using the mirrors as "virtual" sources. This means that it is only necessary to have one central laser rather than lasers at all of the desired peripheral source points. In cases where the cost of installing and instrumenting the support structures can be justified, this method provides a means of monitoring atmospheric species over a range of several kilometers. Two possible applications for such a scheme are monitoring city wide air pollution, and as a large scale gas detector for factories, liquid natural gas storage areas and oil refineries.

SIMULATION OF LASER TOMOGRAPHY

A computer code was written to simulate the scanning action and reconstruction properties of the system described above. This program differs from those employed in modeling normal tomographic reconstructions in two respects: the tapering and shaping of the laser beam and the use of infrared detectors. The radial intensity distribution of a laser can often be approximated by a radial Gaussian function and this intensity dependence is included in the model. In addition, the fan angle of the beam from the virtual source and half power angles for the laser intensity distribution can be specified in the model. This feature allows studies of beam shaping and tapering errors. The second feature allows Monte Carlo simulations to be run to study picture quality as a function of detector signal-to-noise. The user specifies the noise equivalent power and the bandwidth of the detector which in turn sets the amplitude of a Gaussian noise process for noise and signal-to-noise studies.

The code is written in Fortran IV except for some assembly language routines which read the system high precision clocks and set the seed of the random number generator. The program employs fan beam convolution back projection algorithm for reconstruction of the image. The Fortran program writes a disk file which is read by a Pascal program that uses standard dither matrix methods to produce grey scale plots on the lineprinter. A 100 picture ensemble run takes 15 minutes on a DEC system 20 and 90 seconds on a CDC 7600.

SENSITIVITY

Several runs were made to determine the minimum size and strength of a pollution cloud that could be detected. 20 fans with 99 detectors per fan were modelled on a 2 km diameter circle with a 1 km diameter image circle. The laser was assumed to operate at 10.6 microns with an output of 10 watts. The detectors were chosen to be of moderate sensitivity with an NEP of \(10^{-11}\) W/Hz.
and a bandwidth of $10^{+4}$ Hz. The receiving optics was set at a modest 10 cm diameter. With these parameters, it was found possible to resolve a cloud 20 meters across. The minimum measurable concentration was found to lie between 4 ppm and 0.4 ppb. By properly collimating the laser beam in the vertical direction and using detectors with 10 times higher sensitivity, the model calculations showed that it is possible to increase the monitored circle to 10 km with the same sensitivity for a cloud 200 meters across.

PHANTOM RECONSTRUCTIONS

Many reconstructions have been run to test the scanning and reconstruction behavior of the algorithm. Two examples are shown in Figs. 2 and 3. In Fig. 2 a cross-section of a circular disc phantom is shown. The large reconstruction errors are due to the use of only 20 fans in the reconstruction. All other geometric parameters are the same as in the previous section.

![ATTENUATION COEFFICIENT VS DISTANCE](image.png)

**Fig. 2**—Cross-section of the Disc Phantom showing a multicloud phantom reconstruction. Three clouds can be seen in the picture as well as the reconstruction artifacts.

![Reconstruction of Three Pollutant Clouds](image.png)

**Fig. 3**—Reconstruction of Three Pollutant Clouds.

The distance of the abscissa of Fig. 2 corresponds to the distance of Fig. 3 on a side, which is .707 km. Each of the pictures was derived from a 50 by 50 pixel grid. Figure 3 was quantized into 10 levels. In both reconstructions, the clouds were chosen to have integrated densities corresponding to an attenuation of $1/e$. In practice, this is a moderate amount of air pollution.

SIGNAL-TO-NOISE RATIO

Figure 4 shows a plot of estimated signal-to-noise in the reconstruction as a function of laser input power. This data was taken for a system with the same geometric parameters as in previous sections and the cloud shown in Fig. 3. The detector parameters are the same as those of the system in Fig. 1.

The data plotted is the signal-to-noise at the peak of the phantom. The variance of the signal was estimated by taking 100 observations of the pixel fluctuations. It is seen that a signal-to-noise ratio of greater than 100 is obtained for input powers greater than 1 watt continuous wave.
Fig. 4—System Signal-to-Noise Test.

In practice, this is sufficient for television imagery. The beam could be narrowed in the vertical plane to provide a 10 fold boost in the collected energy and reduction in the required laser power. However, the laser power is already well below the current state of the art. Further narrowing is not possible due to the limitations imposed on beam focussing by atmospheric turbulence. Increasing the input power to 10 watts in addition to this beam narrowing would permit increasing the range of the imaged circle to 10 km.

SUMMARY

In this paper we have shown the feasibility of laser scanned computed tomography for regional air pollution measurements. The system requirements are quite modest, especially since the above ranges were obtained using a CW laser. The use of pulse techniques would allow an increase in effective power levels by factors of up to $10^{-5}$. This would permit ranges that are limited by the destruction of the pulse by atmospheric turbulence and not laser input power.

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REFERENCES

