TUNABLE CO_2 LASER-BASED PHOTO-OPTICAL SYSTEMS FOR SURVEILLANCE OF INDOOR WORKPLACE POLLUTANTS

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Abstract

This paper describes research work recently conducted at the National Institute for Occupational Safety and Health (NIOSH) on the use of CO_2 laser lidar for surveillance of indoor workplace pollutants. Long-term goals of this program included an ability to real-time map the spatial distributions of a variety of pollutants in a workplace atmosphere. In pursuit of this goal, a rapidly-tunable, Q-switched, low pressure laser was developed for time-of-flight aerosol backscatter differential absorption measurements. This enabled effective atmospheric freezing as well as the evaluation of possible methods for suppressing the severe multi-reflection scatter problems common in work environments. Experiments were performed to determine the practicality of utilizing aerosol backscatter methods in the desired lidar system. The results of the experiments indicated that present practical technology did not support such a methodology. Other special hardware requirements of a field-deployable lidar system were explored, including high-speed, high-sensitivity detector systems, and miniature detector cryocoolers.

Introduction

During discussions held at the National Institute for Occupational Safety and Health (NIOSH) on research needs for gas and vapor monitoring, industrial hygienists and instrumentation specialists alike voiced a need for portable surveillance equipment to map concentration distributions of selected vapor phase chemical pollutants in the workplace atmosphere, on a real time basis. It was suggested that this should be some type of optical instrument, requiring only line of sight from it to the areas to be monitored. Investigating possible approaches to this task, a number of recommendations regarding the desirable characteristics of a gas and vapor surveillance system were gathered. These recommendations indicated that an ideal system should: (a) be portable (movable into various workplace settings for surveys etc.), (b) be single-ended (no use of retro-reflector arrays or transmitters and receivers separated by large distances), (c) give real-time mapping of the spatial distribution, concentration and identity of a variety of airborne pollutants commonly found in the workplace, (d), not present any hazard to the people in the workplace (from laser radiation, chemicals, liquid nitrogen, etc.), (e) require minimal maintenance (some routine service perhaps every several months), (f) have a sensitivity on the order of 10-100 parts per billion (over sampling distances of five meters) for some pollutants, (g) have a range up to a few hundred meters, (h) be automated and programmable for unattended data gathering, (i) have a spatial resolution of at least five meters full-width-half-maximum (using a point source), and (j) survey the workplace at least every five minutes. In reviewing previous research in this field, two principle methodologies were identified: Fourier transform infrared (FTIR) spectroscopy, and laser-based light detection and ranging (lidar) systems.

Fourier-Transformed Infra-red (FTIR) Systems

Open-beam, long-path FTIR systems appear to be gaining much attention, and showing at least a limited potential for qualitative assessments of atmospheric gas and vapor contents for toxic waste site monitoring, as well as fence-line monitoring. Such a system has been used by Herget for various outdoor studies[1,2] as well as an workroom study in an aluminum refinery potroom.[3]

Other investigators have used FTIR equipment similar to that used in analytical laboratories, for a "real time" analysis of gaseous pollutants in the workplace by use of a multi-port sampling apparatus with sample lines running from work locations to a central FTIR system.[4,5]

FTIR has several advantages over alternate methodologies including: (a) high sensitivity, (b) high specificity, (c) a large variety of chemicals detectable and identifiable, (d) technology is well tested, based on similar laboratory use, (e) proven field ruggedness and dependability, (f) no support requirements other than electricity (if detector cooling is not used), (g) commercial availability, (h) an inherent self-calibration of certain parameters of the equipment, (i) "real time" analysis capability, and (j) portability of the apparatus, making its use for temporary applications feasible. Possible problems associated with this approach include: (a) a lack of an adequate gas phase high resolution spectral library when peak identification methods are used to identify unknown compounds, (b) likely problems with chemical interferences in the analysis, (c) a lack of adequate spatial resolution for some applications, such as measuring breathing zone chemical concentrations, (d) a requirement for either a two-ended system or one using retro-reflectors, (e) a lack of adequate scan speeds to achieve "atmospheric freezing" and, (f) a reduction in the systems sensitivity due to atmospheric water vapor.

Currently, a Nicolet Instrument Co., Madison, Wisconsin, custom portable open beam path FTIR system is being evaluated for industrial hygiene applications by the University of Michigan School of Public Health (S. Levine) and the University of California, Berkeley (R. Spear).[6] This work is being supported by a NIOSH grant #1-\R01-OH02666-01. The Bomem Inc., Quebec, Canada, Model DA2 open beam path FTIR system is currently being used for a variety of atmospheric pollution studies by M. Spartz at the Kansas State University.[7]

Laser Remote Detection Systems

Laser systems have been quite useful in making remote measurements of chemical contents of the atmosphere for a variety of purposes and using several methods. Most remote photo-optical pollution detection work has been accomplished using light detection and ranging (lidar) methods where laser produced radiation was transmitted into the atmosphere to be measured and the return radiation (either aerosol scattered or terrain or retroreflector reflected) is analyzed to obtain the desired information about the chemical contents of the atmosphere. This has been accomplished by a variety of methods[8] including:

a. The analysis of Raman scattered radiation: In this method, Raman scattered short pulses of laser radiation (usually at ultraviolet (UV) and blue wavelengths) are analyzed for their photon intensity <u>vs</u> wavelength distributions as a function of the time from the emission of the radiation pulse from the laser. This results in the identification and quantification of the pollutant of interest as a function of distance from the transmitter. The return signal is relatively weak due to the small Raman scattering coefficient. This limits the range of this technique to a few hundred meters, even using very powerful lasers. Its time-of-flight (the time between a transmitted laser pulse and the return signal pulse, indicating by the time differential what the distance was between the transmitter and a particular scattering or reflecting location) position resolution (ranging) can be on the order of 10 meters. This approach has been used in many investigations, usually to measure pollutants in exhaust plumes from factories or power plants. Raman lidar has the advantage of being applicable to a large variety of pollutants. However, the spectral resolution and bandwidth of the Raman signal is relatively broad leading to significant interferences in complex mixtures of pollutants. Interference often results from sunlight or other bright lighting. Principle limitations are a severe lack in sensitivity of the technique (a very weak Raman return signal) requiring the use of very powerful laser systems which are typically not "eye safe" and would be very difficult to make "eye safe" while preserving the system performance. Also, spatial resolution has been poor due to the poor data statistics of the return signal, and the near field interferences in time of flight measurements.

b. Resonance Absorption Methods: These methods depend on transmitting a laser beam having a wavelength very close to that of a resonance absorption line of a chemical species being measured, and measuring a return signal reflected off of an object or from aerosols in the laser beam's path. It is generally a much more sensitive method then that of Raman scattering due to the much higher scattering coefficient for Mie scattering. This increased scattering coefficient could result in an extended range, the use of lower powered lasers, the use of less sensitive detectors, better range resolution, and faster measurements than Raman lidar. It has the disadvantage of being able to measure only one pollutant at a time when only one laser wavelength is used. Unresolved interferences can result when only one transmitted wavelength is used. One version of such a system uses differential absorption lidar (DIAL) whereby the laser radiation wavelength is shifted between two (or more) wavelengths, one of which is very near to the resonance absorption line of the pollutant being measured and another line which is not. The ratio of these measurements is used to normalize the measurement system calibration with regard to the scattering characteristics of the atmosphere being studied. By measuring the return signal intensity for successive locations along the beam path, subtraction yields the signal loss due to the incremental decrease in the observed signal associated with a range increment ΔR, and arising from the attenuation of the specific molecular constituent for which the laser is tuned. This is described by the following equation:[8]

$$\Delta E_{o*} = [E(\lambda_o,R) - E(\lambda_o,R + \Delta R)] - [E(\lambda_w,R) - E(\lambda_w,R + \Delta R)]$$

where:

ΔE_{o*} = the incremental decrease in the differential signal $E(\lambda o,R)$ = the return signal energy at range R and wavelength λ_o, representing a maximum absorption by the chemical of interest.

$E(\lambda_w,R)$ = the return signal energy at range R and wavelength λ_w, representing an absorption off the resonance line of the chemical of interest.

Using conventional timing methods, DIAL systems can have ranges of several km, and spatial resolutions of as small as 10 m.

Ranging Methods

Principal methods used for position determination (ranging), include: (a) time-of-flight, (b) triangulation ranging (such as methods used by the U.S. Bureau of Mines for measurement of methane gas concentrations at coal seams in mines[9]), and (c) the use of variable focal distance optical systems. Variable focal distance optical systems have been used successfully in laser doppler wind velocity measuring apparatus using CO_2 lasers and heterodyned detection methods, and have produced spatial resolutions of approximately 10 m at a range of approximately 100 m, with maximum useful ranges of up to 1 km. However, this method requires a coherent detection system.[10] Practical problems have been encountered with these systems due to their instabilities and engineering difficulties, including frequency instability, harmonic generation, phase shifted echoes and loss of wavefront parallelism. In addition, there are significant problems associated with the application of coherent detection systems with rapid wavelength shifting, when the parallel retuning of both the transmitting laser and a local oscillator laser must occur or when optoacoustic wavelength shifting of part of the transmitter signals is used as the local oscillator. In addition, coherent detection is probably not practical for short distance time-of-flight measurements (believed to be necessary for our application) due the heterodyne frequencies required to achieve a 30 ns timing resolution. This is especially significant when considering optoacoustic wavelength shifting.

Laser Types

Many laser systems exist for lidar applications, from extremely short-pulse-length, high-energy/pulse systems to continuous-emission, low-power devices covering wavelengths from the far ultraviolet to the far infrared. If a very rugged, low maintenance, compact system is needed, tunable over a range of wavelengths, the number of available lasers becomes quite small. Possible candidates include dye lasers, solid state diode lasers and CO_2 lasers. The dye lasers suffer from rather narrow tuning ranges for a specific dye, moderate to high maintenance requirements and moderate to large sizes. They operate mostly in the near ultraviolet to near infrared region. Operation at those wavelengths may make design provisions for personnel eye protection more difficult due to lower allowable limits of radiation exposure.[11]

Tunable diode lasers are available at less than 1 W outputs covering wavelength ranges from approximately 2 - 30 μm. Significant problems associated with these devices are: (a) a very narrow tuning range, requiring an array of such devices in order to cover a wide wavelength range, (b) high cost, (c) low power output, and (d) large size and weight when a cooling apparatus is included.

Many gases and vapors of interest for monitoring purposes have rich absorption spectra in the near to far infrared, associated with their rotational-vibrational molecular transitions. The CO_2 laser emits radiation in any of about 80 lines in the region 9-11 μm. The number of available wavelengths can be expanded through the use of isotopes of carbon or oxygen in the CO_2. One of these lines can often be closely matched to a rotation-vibration absorption line of a pollutant of interest so that it is feasible to monitor a large variety of compounds (though not necessarily simultaneously). A wide variety of chemicals have been identified as being detectable using a CO_2 laser based lidar system (see Table I for a partial list of gases which can be detected using CO_2 lines[12]). Using rapid tuning, a single laser could presumably be used for differential absorption monitoring of more than a single substance, and under many circumstances, without interference by other vapors or aerosols in the atmosphere. Humidity would be expected to produce little interference in monitoring pollutants in the 9-11 μm region from direct absorption alone. However, in cases where the two differential absorption lines are separated by more than 2 x 10^{-2} μm, moisture effects on the scattering and absorption properties of certain aerosols may become a concern.[13] Other advantages of the CO_2 laser include the potential for a durable, compact and modest costing laser, lacking extensive utility and maintenance requirements, a more liberal allowable irradiance level for laser radiation at long wavelengths vs the UV and visible[11] (this may prove to be an advantage, depending on other system performance factors), and that wavelengths produced by the CO_2 laser are transmitted well through normal atmosphere.

Table I. Partial list of CO_2 laser detectable gases[12]

Name	Wavelength (μm)	Differential Absorption coefficient (atm^{-1} cm^{-1})	Sensitivity (1% diff ab) (ppm-m)
Ammonia	9.2	56	0.9
Benzene	9.6	1.0	50
Chloroprene	10.3	8	6.3
Ethylene	10.5	28	1.8
Freon 11	9.2	11	4.5
Freon 12	9.2	7.6	6.6
Hydrazine	10.8	4.3	12
Methanol	9.7	19	2.6
Monomethylhydrazine	10.3	2.6	19
Ozone	9.6	5.5	9.1
Perchlorethylene	10.7	3.0	17
Trichloroethylene	10.5	3.1	16
Triethylamine	9.6	0.5	100
Asymmetrical dimethyl hydrazine	10.7	0.5	100
Vinyl chloride	10.6	6.5	7.7

A difficulty arises with using infrared radiation rather than visible or ultraviolet in a laser surveillance system using aerosol backscatter signals, because of the lower aerosol backscatter efficiency. As the wavelength is increased, the efficiency of light scattering from aerosol decreases quickly, approximately as λ^{-4}. Therefore, many remote sensing systems designed to provide ranging information have relied on radiation sources other than CO_2 lasers.

In an aerosol backscatter lidar workplace application, the maximum range of interest is on the order of 100 m, compared to the 1-2 orders of magnitude larger in many outdoor applications. As a result, the return light spreading radially from the points of scatter has a short distance for the intensity to drop (falling as $1/r^2$ with distance r). Thus, the limited range needed in the workplace may allow the use of infrared radiation for remote sensing applications.

A literature search revealed no information on the volume backscatter coefficient ($\beta(\lambda, R_o)$) (the parameter characterizing the backscatter efficiency) pertaining specifically to infrared radiation and workplace aerosols. Since the aerosol environment varies considerably from one workplace to another, the backscatter coefficient also will vary.[14,15]

Past Uses of Lidar Systems for Workplace Monitoring

There have been a few attempts in the past to use laser based photo-optical technology for workplace monitoring. In 1981, Britain's Imperial Chemical Industries and G.P. Elliot Electronic Systems, Ltd. made a brief report on a system they were working on using a CO_2 laser-based lidar system for scanning a workplace.[16] To our knowledge this device never was implemented. MDA Scientific, Norcross, Georgia, (formerly Tecan Remote and Environmental Laser Systems), claims to have obtained an exclusive license to use that technology for their applications.

In 1983, Egan of Bethlehem Steel's Homer Research Laboratories reported on the trial of an Er:YAG laser based differential absorption aerosol backscatter lidar for methane detection in mines.[17] In 1985, Litton of the U.S. Bureau of Mines reported on their work in developing a methane monitor using a laser diode operating at 3.3 μm, and a triangulation system for ranging. This resulted from problems with sensitivity and explosion proofing of the equipment, as well as a desire for tunability. Results are not yet available.[9]

In 1985, Persson, at Chalmers University, Sweden reported on a dual CO_2 laser differential absorption detection system for use in a workplace.[18] It used a continuous wave (CW) laser with retro-reflectors placed at the end of the laser beam path. The device measured total column content of the pollutant chemical, thus yielding an average concentration along the path.

Tecan Remote produced a commercial differential absorption CO_2 laser based system for workplace pollutant monitoring.[19] They used a total column content method and retro-reflectors. They have installed systems at some major chemical manufacturers facilities for monitoring around process equipment of special concern. Wavelength changing to monitor different chemicals monitored was possible by a manual retuning of both lasers.

Other photo-optical methods were considered including non-coherent pulsed ultraviolet, visible and infrared sources with sensitive spectroradiometric detection systems. The method seems to be limited by the need for both very intense and very short light pulses when applied to aerosol scattering methods. Generally, adequate high intensity broadband sources having pulse lengths under 10 μs are not yet commercially available. This tends to force the use of long-path measurement methods making use of retro-reflectors, and the acceptance of much poorer spatial resolution. The system's spectral resolution could cause problems in the presence of chemical interferences.

Problems in Applying CO_2 Laser DIAL Lidar Technology to Workplace Monitoring

Based on the above information, it appeared that a CO_2 laser DIAL system had significant potential for leading to a working system that would satisfy most of the system characteristics stated earlier. FTIR methods were also considered promising; however, at least two other research groups were investigating that methodology. Many uncertainties remained in the application of current technology to producing a lidar system satisfying the recommended objectives. These included:

(a) problems in producing a system that can scan a workplace atmosphere while keeping transmitter and receiver beam path alignments precisely co-ordinated,

(b) problems in achieving overall system sensitivities using components that did not require frequent servicing or supplies of materials such as liquid nitrogen, cooling water, etc.,

(c) developing methods for unfolding the identities and quantities of unknown contaminants in complex mixtures, using multiple wavelength measurements,

(d) developing techniques for dealing with data errors due to the effects of rapidly changing aerosol concentrations with time and position. These could contribute to differences in sequential measurements on and off resonance lines,

(e) designing a system that was field portable (that was moveable into a workplace as one or several modules that can be handled by two people). This could place severe restrictions on the equipment selected for use,

(f) designing a system that could operate continuously in an industrial environment without contamination of optical components or without typical temperature and humidity extremes posing a problem,

(g) a significant probability that non-aerosol scattering (scattering from objects and walls in the workplace) could produce a sizeable interfering signal in the detection system, leading to erroneous results or a greatly reduced system sensitivity.

There were significant problems associated with large magnitude non-aerosol scattered return signals from objects in the workplace causing erroneous responses in the receiver. Scatter rejection could be the most severe technical difficulty to overcome. This effect could be reduced by using a coincidence of time-of-flight ranging and triangulation ranging, as well a possible use of both transmitter and receiver polarization for the rejection of multiple scattered return signals (see Figure 1). The triangulation ranging uses a stationary alignment between the transmitted beam and a linear array of receiver detector elements. This fixed transmitter-receiver relationship could also help avoid the difficulty in achieving adequate tracking between a scanning receiver and a stationary or scanning laser beam. In addition, this approach could help to eliminate another potential problem associated with short-range lidar signals, which is a lack of adequate dynamic range in the receiver for return signals arriving from both near and distant scatter sources. By having given detectors look only at a narrow distance range of return signals, acceptable dynamic ranges should result. It was anticipated that combining the narrow field-of-view with time-of-flight ranging would allow a 5m FWHM spatial resolution. It was felt that HgCdTe detectors cooled to liquid nitrogen temperatures might be required here due to the low allowable laser power levels for eye safe conditions, as well as many other demands of the system design.

Calculations for a specific system were performed, using values for variables suited to the desired system performance. The choice of values for these variables resulted from a review of the specifications of available components and subassemblies (including a consideration of their costs). An example can be seen in Appendix I. The calculations show that we would need a single pulse energy of 2.75×10^{-3} J for the system to function under the conditions defined. The stability of the system's electronics and optical equipment may limit reliable differential measurements to 1 to 2 percent;[12,20] consequently, signal to noise ratio (SNR) values greater then 500 to 1000 may not be useful.

The results of these calculations indicated that if the assumptions used were correct, it would be possible to produce a lidar system having the required sensitivity, beam irradience, pulse energy, etc. However, these calculations: (a) assumed a hypothetical value for the volume backscatter coefficient ($\beta(\lambda_0, R_0)$) which may not represent workplace conditions well, (b) did not address large scattering signals from surrounding objects, (c) assumed perfect performance of optical and electronic components, (d) did not address interfering chemical species, (e) did not address pulsed electrical noise from the laser and Q-switch being introduced into the detector signal, degrading the systems SNR, and (f) assumed that the limited information on detector D^* values were valid for the fast signals necessary for the time-of-flight measurements required.

Equipment and Methods

Laboratory Test System

Based on the review conducted, and the potential benefit of a workplace pollutant monitoring system based on a DIAL system, a laboratory evaluation was conducted of certain aspects of a CO_2 laser workplace DIAL system using time-of-flight and triangulation ranging. In order to make measurements of certain un-evaluated parameters relative to the performance of the lidar system, to verify the practicability of certain design concepts, and to provide for experimental development of a working system, a laboratory test system was assembled. The goals in designing this system were to construct a laboratory apparatus having a maximum flexibility to evaluate various methods of assembling a workable lidar system. It also needed to be capable of measuring many of the system parameters necessary for tne development of future designs of a field useable system.

The laboratory test system consisted of the following subassemblies:

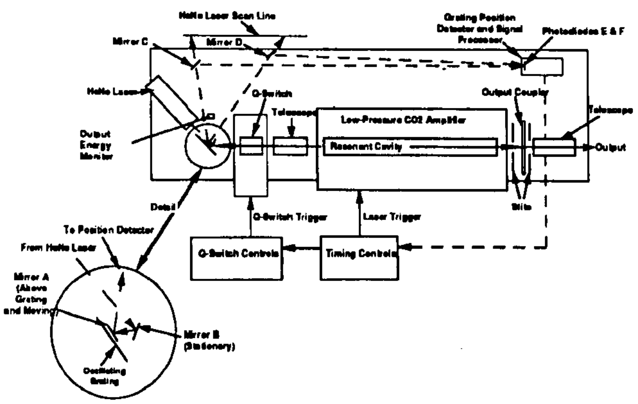
Laser

System performance goals necessitated the use of a recently developed low pressure pulsed CO_2 laser in combination with a high performance intercavity Q-switch for producing near-Gaussian (no tailing as is associated with TEA CO_2 lasers), short, high-intensity pulses. In differential absorption lidar systems, it is important that differential absorption measurements in an atmosphere take place on and off of the resonance line of the chemical compound of interest, with a very short time interval between the two measurements. In the past, this has been accomplished by using multiple lasers tuned to different wavelengths, fired sequentially with a short time interval between pulses[20]. It was considered desirable that the two pulses of the pair be produced by the same laser, lowering equipment size, weight, costs and alignment problems.

Rapid wavelength changing of a single laser could allow for a rapid change of chemicals monitored, thus allowing a more frequent monitoring of pollutants of interest. This has not proved to be practical in the TEA lasers typically used, due to both power supply constraints as well as the mechanical behavior of the lasing medium. It was also desirable that the laser be compact, require a minimum of cooling, have an extremely long lifetime (greater that 5×10^7 shots), and use low radio frequency interference (RFI) components.

A laser was constructed using a modified Pulse Systems, Los Alamos, NM, model LP30 low pressure CO_2 amplifier section, due to the long upper lasing level lifetime (greater than 60 ms) of low-pressure CO_2 lasers. This lifetime permitted the Q-switching of two output pulses from a single laser amplifier electrical transverse discharge pulse, while allowing several microseconds for wavelength changing between pulses. An intracavity beam telescope was employed to use the amplifier discharge cavity cross-section efficiently with the small CdTe Q-switch crystals available. A 1200 Hz oscillating grating with a high-resolution grating position sensor was used to change and reprogram wavelengths rapidly. Programming of wavelengths was accomplished by selecting appropriate delay times from the grating position reference signal for triggering the laser amplifier and Q-switch (see Figure 1). The resulting laser was relatively compact and had a low mass, and low power consumption. It had output pulses of approximately Gaussian shape with full-width-half-maximum values adjustable between 50 and 100 ns; an ability to produce "pulse pairs" having interpulse spacings of 5-50 μs, each pulse of the pair being independently wavelength selectable over most CO_2 laser emission lines; a repetition rate for the "pulse pair" up to 10 Hz;, a pulse energy of approximately 5-10 mJ; and pulse pair wavelengths reprogrammable between pulse pairs. The output of the laser was emitted through a beam expanding telescope such that the irradience was well below maximum permissible occular exposure limits[11] for the pulse widths and repetition rates used. Most of the basic performance goals of the device were achieved in the laboratory prototype. A full description of this laser is presented in a paper soon to be published.[21]

FIGURE 1. Q-SWITCHED DOUBLE-PULSE CO_2 LASER



Beam Power/Energy Monitor

Provision was made for extracting a fixed percentage of the output beam to a beam power and energy monitor. The beam power/energy monitor was used for continuously monitoring the beam pulse-to-pulse energy differences to normalize the results of differential absorption measurements to constant beam pulse energy conditions. This monitor consisted of a fast (<1 ns rise and fall time) room-temperature HgCdTe detector (Boston Electronics Corp., Boston, MA, model R004-0) and a Comlinear Corp., Loveland, CO, model CLC100 low noise amplifier. The monitor had a short term (1 h) reproducibility better then ±1.0 percent and an absolute long term accuracy better then ±5 percent (2σ). This detector monitored the laser output radiation intensity and waveform via radiation reflected from the tuning grating.

Receiving Telescope

The receiving telescope was a Newtonian type having a mirror diameter of 8 inches and an effective aperture of approximately f/4.5. It was used for gathering the return signal laser radiation and projecting a line image of the aerosol scattered laser beam onto HgCdTe detectors.

Detectors

Several types of detectors were available for sensing radiation in the 9-11 μm wavelength band; however, only the HgCdTe detectors had sufficiently high detectivities (as indicated by D^*) for use in this application. HgCdTe detectors are manufactured in a variety of forms, varying in surface area, wavelength sensitivity, frequency response, etc., depending on their applications. Unfortunately, the manufacturers' data on their products were often sketchy, and their testing methods often did not include actual measurements of fast pulses of radiation. Thus, one was often left to speculate on their actual performance in a particular application. Competing performance parameters, frequency response and detectivity, were both critical to the function of the lidar concepts to be evaluated. The detectors evaluated in the receiver system were cooled HgCdTe detectors of photovoltaic (77 K) and photoconductive (77 K and 200 K) types, and were selected as representative of devices commercially available at the time. The photoconductive detectors were specified to have approximately 10 degree fields of view, 1.3 x 1.3 mm size, D^* values of approximately 1×10^{11} cm $Hz^{1/2}$ W^{-1} at 10 kHz, and a high frequency roll-off at approximately 10 MHz. The elements were useable as single elements or as a linear array with 5 elements. Element six was a photovoltaic detector 1 mm diameter, had a 10° field-of-view, a D* rating of 2 x 10^{10} cm $Hz^{1/2}$ W^{-1} at 100 kHz, and a high frequency roll-off at approximately 50 MHz. The detector array was manufactured by InfraRed Associates,Inc., Cranbury, NJ, as their model #89-251R. For very high-speed measurements (<10 ns rise and fall times) a Judsen model J15TE4:10-MC31G-S01M thermoelectric cooled (200K) HgCdTe photoconductive detector with a model TC-4 controller (both manufactured by EG&G Judson, Montgomery, PA) was used. It had a 1 mm diameter detector element, a D* rating of 3 x 10^8 cm $Hz^{1/2}$ W^{-1} at 10 kHz, and a high frequency roll-off at approximately 100 MHz. Generally, the HgCdTe detectors designed for higher operating temperatures exhibited much better frequency responses, but this is accompanied by a significantly lower D* value. Due to the photovoltaic detectors large capacitances and consequential long time constants, a Comlinear model AJP401 transimpedance preamplifier was used to help reduce the effective time constant. Comlinear Model CLC100 video voltage preamplifiers were used with the photoconductive detectors.

Detector Cooling

The detectors used for detecting return signals were cooled by two methods. The linear array detector was kept at its operating temperature (45-77 K) by a closed cycle miniature refrigeration system (a Philips/Magnavox Model MX 7043, Magnavox Electro-optical Systems, Mahwah, NJ). This consisted of a split Stirling cycle, linear motor device using no bearings or lubricants, and having clearance seals. The overall device was hermetically sealed. Mean times between failures for this device are guaranteed to exceed 2500 operating hours, with test data implying lifetimes >10,000 h. Heat power capacity at 77 K was approximately 1 W, allowing reasonably large assemblies of detectors to be cooled. Total power consumption at those operating conditions was approximately 50 W. The vibration produced by the mechanical refrigerators can cause unwanted motion in the detector, which may degrade system performance by modulating the detector's position relative to the focused photon beam to be detected. The satisfactory performance of such a closed-cycle cooler could provide a considerable advantage to the performance of a field-deployable workplace lidar, allowing the utilization of high sensitivity detector systems without the difficulty of supplying liquid nitrogen for it. The single element photoconductive detector (see identified in "Detector" section) was cooled to 200 K by a four-stage thermoelectric cooler. Such coolers had extremely long expected lifetimes, produced no vibration and required little power (8 W for the one used). The lower temperature limit of such coolers resulted in a less than optimum D* value for the detector, when detection sensitivity at very high frequencies was not critical.

Transient Waveform Analyzer

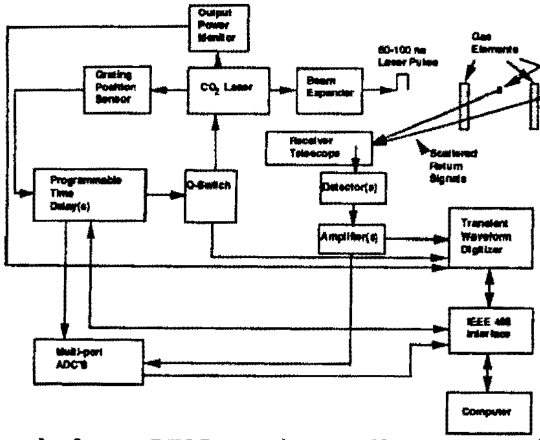
A high speed waveform analyzer was needed both for general system diagnostics as well as for analyzing lidar return signal time of flight information. This consisted of two LeCroy Corp., Spring Valley, NY, Model TR8828 Transient Waveform Recorders, capable of capturing two fast waveforms simultaneously and recording them in temporary memory. These recorders digitized the waveform information in 5 ns increments, with an 8-bit accuracy, and stored the information in file lengths up to 32k. These recorders were interfaced via a CAMAC IEEE-488 interface to a data processing system for display and data reduction. ASYST waveform analysis software (Asyst Software Technologies, Inc., Rochester, NY) was used to display and treat lidar return signal data. A specialized fast-Fourier-transform filtration method utilizing a Blackman attenuation function[22] was used to remove unwanted high frequency components of the data, allowing a better extraction of return signal information. After using a wide range of cutoff frequencies with the data, a 30 ns cutoff was selected which, considering the slope of Blackman filter function, appeared to have an effective frequency cutoff of approximately 100 MHz. Some data were recorded using a model 54021A oscilloscope manufactured by Hewlett Packard Co., Palo Alto, CA.

Data Logger

A data logger consisting of at least 12 parallel channels of fast sample and hold amplifiers coupled to 10 bit ADC's, was interfaced to the data processing system via a CAMAC IEEE-488 interface. The sample and hold amplifiers had gate times as small as 10 ns. This enabled the setting of individual time of flight range windows for individual detectors in a linear array, and a rapid shift of signals from one set of input channels to another between short-interval pulse-pairs.

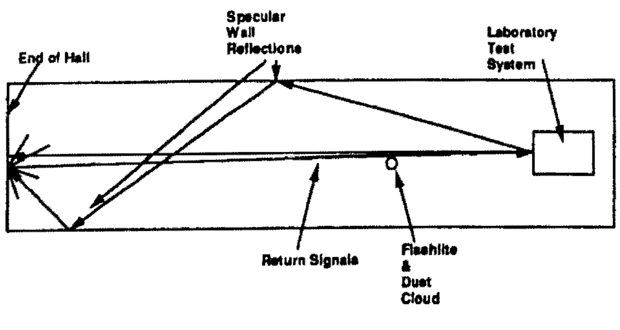
With the assembled laboratory test system (see Figure 2), a series of experiments was performed to help to understand better the potential for using aerosol backscatter as a signal source for a

FIGURE 2. LABORATORY TEST SYSTEM.



workplace DIAL system. Measurements were carried out in a corridor having dimensions of 1.85 x 2.75 x 79 m. Major components of the laboratory test system were mounted on a movable bench positioned at one end of the corridor. The transmitted laser beam was then projected along the major axes of the corridor under several conditions (see Figure 3) including: (a) co-axial with the corridor and intercepted by the end of the corridor;, (b) as in (a), except with an object (a light source mounted on a tripod), and separately, a generated aerosol (wood dust, and bleached flour) in the beam path located 28m from the source; (c) with the laser beam projected to reflect off the walls of the corridor, as well as the end of the corridor. Return signal measurements were made using both the thermoelectric-cooled and

Figure 3. Corridor Measurements Using Laboratory Test System.



Stirling-cycle-cooled detector systems, located at the focal point of the receiver telescope for particular distance intervals along the transmitted laser beams path. The profile of the transmitted laser beam was mapped at a position approximately 28 m from the transmitter, using the thermoelectric-cooled HgCdTe detector operated above its normal operating temperature of 200 K, to reduce its efficiency. The detector was scanned in 2.5 cm intervals from -15 to +15 cm along both the x and y axes on a plane orthoganal to the beam axes. Measurements were made at 10.6 µm wavelength (10P20 line), with a laser output of approximately 2 mJ/pulse. Measurement of the overlap of the receiver acceptance angle and solid angle of the transmitted beam at a given focal distance were made by scanning the detector element across the focal plane for a point reflector backscatter source located at the extremes of the beam cross section. This was accomplished at distances from the transmitter/receiver of 15 and 28 m.

Data and Discussion

Table II shows the transmitted beam cross section relative irradiance profile.

Table II. Mapping of the Relative Irradiance of the Laser Beam Cross Section at 30 m.

Relative Irradiance (W cm^{-2})

Y-axes (cm)	-12.5	-10	-7.5	-5.0	-2.5	0	2.5	5.0	7.5	10	12.5
-12.5					0	0	0				
-10				0	15	50	25	0			
-7.5			0	15	60	100	70	25	0		
-5.0		0	25	175	270	300	250	50	0		
-2.5			0	100	200	250	210	25	0		
0	0	0	50	125	250	275	175	25	25	0	
2.5			0	50	175	300	225	15	0		
5.0				0	50	150	75	20	0		
7.5				0	15	50	25	0			
10					0	0	0				
112.5											

From the slight bipolar shape, it appears that there are probably two cavity resonance modes present. Figure 4 shows the output from the laser as measured by the 200 K detector. The approximately 6 µs interval between two sequential pulses on the 10P16 and 10P20 lines respectively can be seen. Figures 5a-5c show the return pulse (diffusely reflected from an object at 10 m) as monitored by a photoconductive detector element (77 K), a photovoltaic detector element (77 K), and a photoconductive (200 K) thermoelectrically cooled detector respectively. It should be noted that the polarity of the pulses shown in Figure 5 varies with the detector and amplifier used. The output of the 77 K

Figure 4. Dual-pulse Laser Output.

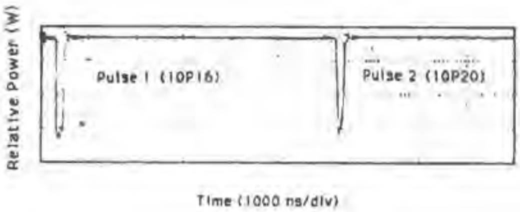
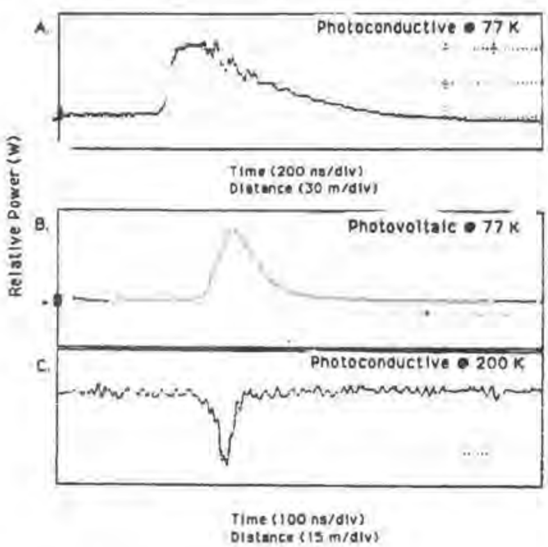


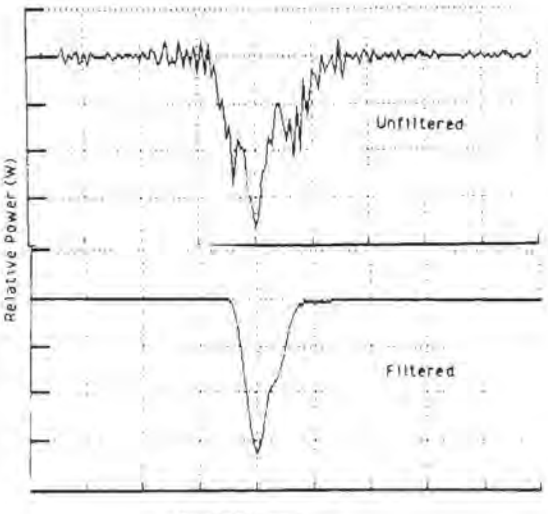
Figure 5. Frequency Response Characteristics of Three Types of HgCdTe Detectors.



photoconductor and photovoltaic detectors is positive-going, and the 200 K photoconductive detector is negative-going. It is clear that the frequency response of the photoresistive detector is quite poor, with a 1/e time constant of approximately 500 ns. The 77 K photovoltaic detector frequency response was much better, with a 1/e time constant of approximately 80 ns. The frequency response of both of these detectors was somewhat poorer than anticipated. Manufacturer D* specifications for their detectors are often based on low frequency measurements (1 - 10 kHz) and extrapolated to higher frequencies, with possibilities for substantial errors. Pulse shape distortions by the detectors for fast rise and fall time pulses were often not specified by the manufacturer. The time constant of the 200 K photoconductive detector was small enough (specified as <10 ns by the manufacturer) that the laser pulse shape detected by it was not easily distinguishable from that displayed from the high-speed room-temperature HgCdTe detector. Examining the time resolution required for a 10 m time-of-flight (round-trip for the desired 5 m spatial resolution, approximately 33 ns), it seems apparent that, based on frequency response alone, the 77 K photovoltaic detector would be quite marginal, since tailing in its output pulse excessively extended over neighboring spaces, and only the 200K and room temperature photoconductive detectors would be fully adequate. Considering that 60 ns FWHM is probably a lower limit for the transmitted laser pulse width, any further degradation of that pulse width would be unacceptable. It should be noted that it would be difficult to achieve a 5 m spatial resolution from a continuous aerosol backscatter source using time-of-flight methods and a 60 ns FWHM transmitted pulse. We anticipated that the combination of triangulation and time-of-flight could make this possible). Examining the D^* ratings of these detectors, it is clear that substantial system design compromises would be necessary to utilize either one, with the room-temperature device being particularly poor. Considering the above findings, it appears that the earlier use of a D^* value of 1×10^{11} cm $Hz^{1/2}W^{-1}$ in the example calculations was overly optimistic, and that in practice a value of 10^8 cm $Hz^{1/2}$ W^{-1} may be more realistic. This is a result of both the pulse shape distortion resulting from some detectors, as well as an inaccurate extrapolation of D* values to higher frequencies. It is possible that this could be improved by the use of lower capacitance photovoltaic detectors, detectors with a much smaller surface area, or the use of coherent detection methods. The use of much smaller surface area detectors would demand a much more sophisticated optical assembly to achieve a sufficiently stable focus of the return photons on the appropriate detector element. Some practical improvements could probably be achieved with this; however, their magnitude would be difficult to estimate. Additional system sensitivity improvements could be achieved by increasing the receiving telescope diameter (a 30 cm diameter would increase A_0 by a factor of 2), and by increasing laser power (narrowing safety margins to 400% should allow an increase by approximately a factor of 10) to approximately 25 mJ/pulse. Both the closed-cycle Stirling cooler and the thermoelectric cooler worked well during the several hundred hours of operation they were used.

The curves in Figure 6 show the effect of filtration on a single return pulse. Figure 7 shows the overlap of an end-of-corridor return signal with a space separated from it by 20 meters, using the high-speed 200 K HgCdTe detector, and an approximately 90 ns FWHM transmitted pulse. The ratio of the end-of-corridor signal to the adjacent space along the beam path (assumed to be an insignificant signal for the aerosol backscatter component) is approximately 300. Sources of this unwanted signal may include stray light, aberrations in the receiver optics, inadequate collimation of the detector, and the shape and width of the transmitted pulse.

Figure 6. Example of Filtration of Single-pulse Waveform.



If the ratio of the aerosol scattered signal to that from a diffusely reflective surface is approximately 10^{-4}, it appears that the return signal from a space adjacent to such a strong signal would have to be isolated from that signal source by a ratio of at least 10^{5}, in order for aerosol backscatter from the space to be detectable and useful. Depending on the aerosol concentration and its reflective properties the aerosol scattered signal could vary over several orders of magnitude. It appears from the data in Figure 7 that the "tails" of the very strong specular or diffuse reflections from walls or other solid objects cause overlaps of signal in neighboring spaces such that the resulting SNR ratings for the adjacent space along the beam path would be inappropriate for detection of aerosol backscatter signals.

Figure 7. Effect of Large Signal Source on Detection of Neighboring Small Signal Source.

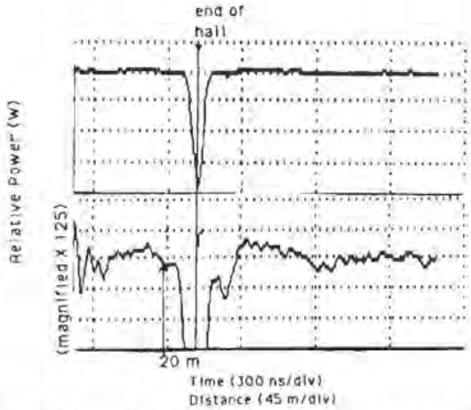


Figure 8 shows an example of an aerosol backscatter signal produced by a fine mahogany wood dust aerosol along an approximately 3 m pathlength of the laser beam, at a distance of approximately 28 m from the transmitter/receiver. The waveform was the result of the subtraction of a return signal without added aerosol from one with the added aerosol. The limiting background noise in the signal appeared to be the result of electrical noise from the Q-switch induced into the detector signal path, rather than amplifier and detector noise. This aerosol was poorly characterized; however, it very likely represented wood dust levels in excess of OSHA allowable limits (a visible cloud). This experiment was used to produce an example of an upper practical limit of the amount of backscatter signal that could be obtained. Normal aerosol concentrations in the air-conditioned laboratory space were insufficient to observe aerosol backscatter with the receiver efficiency and transmitted laser power of the present system.

An examination of the difficulties in using aerosol backscatter as a signal source for a workplace DIAL system prompted an examination of alternatives. The above data suggest that the scatter from workplace objects and walls could provide a strong signal source for a "column content" system. Time-of-flight return signals, such as in Figure 9, could be cross-correlated with the transmitted signal to enhance the separation of return pulses having differing time-of-flight values, thus enabling a determination if only one significant scattering of the transmitted

Figure 8. Backscatter From Wood Dust Aerosol.

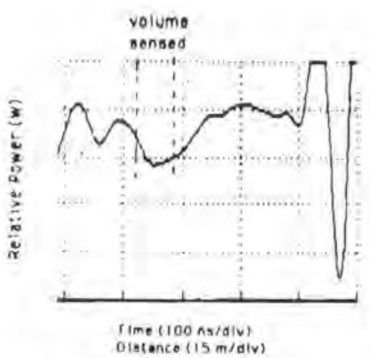
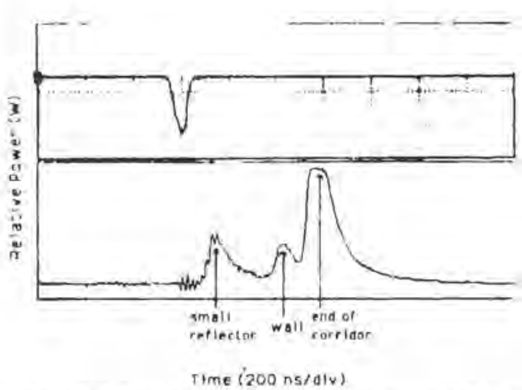
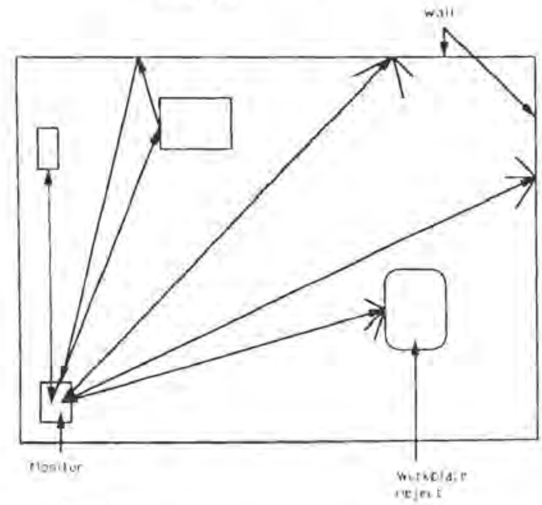


Figure 9. Multiple-scattered Return Signal.



signal had taken place, as well as to determine the round-trip path length of the transmitted pulse to the receiver (see Figure 10). The continuous radial scanning of a workplace utilizing this methodology may provide a useful means of generating an angular mapping of average beam-path concentrations in the workplace. The use of more than one transmitter/receiver system, having overlapping monitoring fields, could allow construction of a workplace pollutant concentration map. It is also possible that an aerosol backscatter signal could be used if the reflective surfaces the beam could intercept were treated to reduce their refectivities (perhaps by a few orders of magnitude), or in outdoor workplaces where no significant non-aerosol backscatter sources were in the field-of-view. Outdoor settings should also provide a substantially larger backscatter coefficient.

Figure 10. Radial-scanning Workplace Monitor



Conclusions

This study identified several substantial limits to the use of an aerosol-backscatter DIAL system for workplace monitoring. These were (a) the limitations of currently available detectors, when applied to a high spatial resolution time-of-flight lidar, (b) the difficulty in providing very high optical isolation ratios for adjacent spaces along the laser beam, (c) the probable low aerosol concentrations for air conditioned workplaces (compared to outdoor concentrations),[14] and (d) the difficulty in eliminating induced signals from the laser Q-switch into the receiver electronics. Of these, (b) is probably the most difficult problem to correct. A consideration of these basic problems identified in the use of aerosol backscatter as a means of providing a continuous source of return signal leads the author to conclude that present practical technology precludes such a methodology. Outdoor workplaces without non-aerosol backscatter sources in the field-of-view could be a suitable setting for using aerosol backscatter methods. As an alternative, it appears that the use of backscatter from workplace objects may provide a useful means of generating an angular mapping of average beam-path concentrations in workplace. Further work is needed to indicate the viability of this approach.

Acknowledgment

The author wishes to acknowledge the efforts of Gregory J. Deye, physicist, for his work in the difficult task of adapting the Asyst software to the requirements of the data output of the laboratory test system, and David Bartley, research physicist, for his initiation of the concept for this project. Both are employees of the Division of Physical Sciences and Engineering, the National Institute for Occupational Safety and Health, Cincinnati. Ohio.

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APPENDIX I

From Measures[8]

$$E^{min} = \frac{2R^2 \quad (SNR)^{min}}{\beta(\lambda_o,R)\ \xi(R)\ A_o\ \xi(\lambda_o)\ \Delta R\ D^*\left(\frac{4B}{A_d}\right)^{1/2}} e^{2\int_o^R k(\lambda_o,R)dR}$$

where:

E^{min} = minimum laser energy pulse required to observe a return signal at range R (J)

R = range to ΔR being sensed (cm)

ΔR = range interval being sensed (cm)

SNR^{min} = signal to noise ratio

$\beta(\lambda_o,R)$ = volume backscatter coefficient $cm^{-1}\ sr^{-1}$

$\xi(R)$ = overlap factor of laser and receiver beam (geometric form factor)

λ_o = wavelength of resonance line at which laser is operating (cm)

A_o = area of objective lens (cm^2)

$\xi(\lambda_o)$ = receiver spectral transmission factor

τ_d = detection time interval (s)

D^* = specific detectivity (cm $Hz^{1/2}\ W^{-1}$)

$k(\lambda_o,R)$ = normalized attenuation coefficient for pollutant in atmosphere (STP) $(ppm\ cm)^{-1}$

C = concentration of pollutant (STP) (ppm)

B = detection bandwidth (sec^{-1}) ($=1/2\tau_d$)

A_d = detector area (cm^2).

Using the following values for variables in the previous equation:

R = 10,000 cm

ΔR = 500 cm

SNR = 1.5

$\beta(\lambda_o,R)$ = $10^{-8}\ cm^{-1}\ sr^{-1}$ (this value may be much higher in an industrial atmosphere or lower an air conditioned atmosphere)

$\xi(R)$ = 1.0

λ_o = 9.639 μm

A_o = 314 cm^2

$\xi(\lambda_o)$ = 1.0

τ_d = 5×10^{-8} s

D^* = 10^{12} cm $Hz^{1/2}\ W^{-1}$ (10^o acceptance angle) (practical values for this variable using non-coherent detection are probably on the order of 10^{11})

$k(\lambda_o)$ = $2.4 \times 10^{-6}\ ppm^{-1}\ cm^{-1}$ (Benzene at 1ppm cm^{-1}) (other compounds may have values up to 10^2 times that for benzene)

C = 1 ppm

A_d = $1.7 \times 10^{-2}\ cm^2$ (0.05" on side).

Then,

$E_L^{min} = 4.13 \times 10^{-6}$ J

If 10 sequential shots are accumulated, then:

$\tau_d = 5 \times 10^{-7}$ s

and

$E_L^{min} = 1.3 \times 10^{-6}$ J per shot

$$N_i^{min} = \frac{1}{2\ \sigma^A(\lambda)\ \Delta R} \ln\left(1 + \frac{1}{(SNR)^{min}}\right)$$

$$C_i^{min} = \frac{N_i^{min} \times 10^6}{N_{atm}}$$

$$C_i^{min} = \frac{1}{2\sigma^A(\lambda_o) N_{atm}\ \Delta R} \ln\left(1+ \frac{1}{(SNR)^{min}}\right) \times 10^6.$$

The attenuation coefficient $k_A^i(\lambda_o)$ (cm^{-1}) of component i under atmospheric condition of interest is given by:

$$k_A^i(\lambda_o) = \sigma^A(\lambda_o)\ N_{atm}$$

Therefore,

$$C_i^{min} = \frac{1}{2k_A^i(\lambda_o)\ \Delta R} \ln\left(1+ \frac{1}{(SNR)^{min}}\right) \times 10^6$$

Where

$\sigma^A(\lambda_o)$ = absorption cross section of the molecular constituent of interest at wavelength λ_o (cm^2)

C_i^{min} = threshold concentration that can be detected (ppm)

N_i^{min} = threshold number density of species i that can be detected (molecules cm^{-3})

N_{atm} = total number density of molecules in atmosphere under atmospheric conditions of interest (molecules cm^{-3})

For

SNR = 1.5,

$k_i^A(\lambda) = 2.42\ cm^{-1}\ Atm^{-1}$ (for benzene STP)

$\Delta R = 500$ cm

$N_{atm} = 2.55 \times 10^{19}$,

then

$$C_{benzene}^{min} = \frac{1 \times 10^6}{4(2.42)(500)} = 207 \text{ ppm},$$

and we would need a single pulse energy of 6.1×10^{-6} J.

If

SNR = 1000,

then,

$C_{benzene}^{min} = 0.41$ ppm,

and we would need a single pulse energy of 2.75×10^{-3} J.

DISCUSSION

CHUCK FLYNN: I'm curious about the decision, or finding, that it was not useful because of the near scattering effects. If you could do away with this scatter, would it be desirable?

HARLEY PILTINGSRUD: One of the things I mentioned in the paper, and didn't have time to mention here, was that there possibly are some options in some workplace situations where you could attenuate the backscatter from objects in the workplace by some treatment. But it would be a little difficult because you'd have to reduce it by a couple orders of magnitude and that's not real easy to do.

CHUCK FLYNN: And if you took away the desire to do your ranging, could you then do it easier?

HARLEY PILTINGSRUD: As I mentioned the second approach is one where you lose some ranging. You know the direction the beam is pointed but the measurement is a total column content one, so you don't know how the concentration varies along the beam path. By using two such systems at different angles of view, you could achieve some two-dimentionsal spatial resolution.

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