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LIDAR for Detection of Chemical and Biological Warfare Agents

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ABSTRACT

Remote detection of chemical and biological warfare agents and toxic gases in the atmosphere is of current interest to both the military and civilian agencies. Out of all currently available techniques, no single technique provides efficient detection against such threats at significant standoff distances. Light detection and ranging (LIDAR) technologies, based on the transmission of laser pulses and analysis of the return signals, have demonstrated impressive capabilities in remote detection of such toxic chemicals. LIDAR is a highly sensitive tool to detect the extremely low concentrations of various toxic agents present in the form of thin clouds at distances of few kilometer. The detection of these toxic clouds is based on the approach of first detecting and measuring the range of the clouds using the scattering phenomena and subsequently identifying the composition of toxic clouds using absorption and fluorescence phenomena. Laser Science and Technology Centre (LASTEC), Delhi has been working on the design and development of LIDAR systems for detection of chemical and biological warfare (CBW) agents. In this paper, theoretical analysis of differential absorption LIDAR (DIAL) for detection of chemical agents and fluorescence LIDAR for detection of biological agents has been discussed. For some typical parametric conditions, the received power levels from different ranges to detect specific concentrations of chemical or biological clouds have been computed and discussed. The technical details of the indigenously developed backscattering LIDAR, which detects and measures the distance of cloud layers up to 5 km is also presented.

Keywords: Light detection and ranging, LIDAR, differential absorption LIDAR, UV LIF LIDAR, chemical and biological warfare agents, ranging

1. INTRODUCTION

The use of chemical and biological warfare (CBW) agents against civilian and military by terrorist and rogue countries is very frequent in these days[1,2]. The sarin attack by the Aum Shinrikyo cult in earlier 1995 at Tokyo subway and hydrogen cyanide, mustard gas attack by Iraq in its Anfal Campaign against the Kurds, most notably in the Halabja Massacre in 1988 are the few recent examples[3]. Terrorist attacks against the United States on 11 September 2001, coupled with the havoc caused by the intentional dispersal of anthrax spores has attracted renewed attention to the potential for biological agents to be used as weapons[4]. These incidents have increased worldwide awareness of early detection of chemical and biological warfare agents. Among all chemical warfare (CW) agents, nerve (organophosphonate compounds) and blister agents (mustard compounds) have been identified as the potential threatening agents because of their acute toxicity[5]. These agents initially stimulate and then paralyse certain nerve transmissions throughout the body and cause other toxic effects such as seizure, etc. In contrast to CW agents, biological agents (BA) are the naturally occurring or engineered bacteria, viruses, chlamydiae, rickettsiae, fungi, and biological toxins[6]. The use of BAs as weapons is a serious threat for several reasons. They have the ability to multiply in the human body and significantly increase their effect. Many BAs are highly virulent and toxic; they have an incubation period (their effects are not seen for hours to days after dissemination) and some can be transmitted from person to person. Significant advances in the areas of molecular biology and biotechnology over the past quarter century have made the tasks of detection and treatment of BAs all the more difficult. Biological agents have often been described as the poor man's bomb. This may be due to the fact that BAs are relatively cheap to make because all that is usually involved is growing organisms that are found naturally in lot of cases.

CBW agents are more commonly delivered in the air, using systems that have four major components: payload (the chemical agent, often with a solvent or carrier chemical depending on the agent), munition (container that keeps payload intact during delivery), delivery system (missile, artillery shell, aircraft, UAV, etc.), dispersal mechanism (an explosive force or spray generator to dispense the agent into the air, where it can reach the target population). Once the CBW agents are delivered from an artillery shell, they start dispersing in the atmosphere with the background wind speed. For example, CBW cloud released at the height of 1 km takes 100s to reach the ground if it disperses with wind speed of 10 m/s. Hence, it is required that the response

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time of the system must be faster than that of the cloud spreading. A secondary purpose for a system could be to track the cloud and find the source of release, thereby having a potential to defeat the enemy behind the attack. These CBW agents are highly toxic and infectious in very low doses. Therefore, CBW agents detection systems need to exhibit high sensitivity (i.e., be able to detect very small concentrations of CBWs). The complex and rapidly changing environmental background also requires these detection systems to exhibit a high degree of specificity (i.e., able to discriminate from other harmless materials present in the environment). A third challenge that needs to be addressed is speed or response time. These combined requirements provide a significant technological challenge.

LIDAR (light detection and ranging) is the only realistic method for standoff CBW agent detection today and uses lasers as excitation source[7]. LIDAR systems are superior to point-detection systems (infrared spectrometry, Raman spectrometry, FTIR, etc.) because of their capability of ranging and discriminating the CBW molecules in real time[8]. The detection method can be based on several physics phenomena. The most common phenomena are elastic backscattering, laser-induced fluorescence, and differential absorption. A LIDAR using elastic backscattering[9] could detect a CBW cloud at a long distance. Ultraviolet laser-induced fluorescence (UVLIF) could be used for classification of the biological molecule, since most BW agents and toxins fluoresces when excited with UV radiation[10,11]. Differential absorption method uses two infrared laser wavelengths to detect CW agents: one corresponds to peak absorption of chemical molecule and other corresponds to weak absorption. The ratio of these two signals gives concentration of particular CW agent[12,13]. At LASTEC, the authors have been working on the project, "Development of multiwavelength LIDAR system for detection of chemical and biological warfare agents". To their knowledge, this system is the first of its kind in technology, which is being developed at LASTEC for detection of CBW agents. The technical details along with some typical results of the backscattering LIDAR system operating at 1064 nm, which was designed and developed in-house are presented. Also, the results of the theoretical studies carried out for the development of differential absorption LIDAR (DIAL) and ultra violet laser-induced fluorescence LIDAR (UV LIF) for detection of CBW agents are discussed. These two systems are being developed as stand-alone independent units.

2. DETECTION APPROACH

CBW agents are more commonly delivered close to the ground, preferably within the altitude region of few hundred meters using the system like rocket shells, missile, UAV, etc. The prevailing atmospheric dynamic processes (wind speed) make them to spread both vertically and horizontally to form stratified layers/clouds in the atmosphere. Lifetime of these clouds can be from an hour to a day depending upon its nature. In course of time, these clouds settle down and thereby cause health hazard to plants, animals, and human beings. Hence, it is emphasised that the continuous monitoring of the atmosphere is very important. LIDAR system plays a vital role in detecting and identifying these clouds in the atmosphere. A backscattering LIDAR operating at 1064 nm based on Mie scattering principle can search the suspected atmospheric region to look for upcoming clouds though it cannot identify its composition and concentration. The backscattering LIDAR with proper combination of pulse energy, pulse repetition frequency and suitable receiver optics, can differentiate the cloud-return signals from the background atmosphere. It is expected that this system could detect the presence of clouds at distance of 2-5 km depending on the cloud concentration and weather conditions. A potential LIDAR system contains multiwavelength laser source (UV (266 nm and 355 nm), 1064nm and mid-IR (3-4 μm) wavelengths), common transreceiver and scanning gimbal, computer controllers with graphical user interface (GUI). The LIDAR master computer controls the system functions like laser operation, search and classification modes by sending commands to the scanner head, LIDAR processor which captures and processes the LIDAR signals wrt spatial and spectral informations. In search mode of operation, a common scanning gimbal mirror transmits 1064nm laser radiation continuously into the atmosphere. The backscattered radiation collected by scanning mirror is sent to optical telescope. Further, this radiation is focused onto an appropriate detector. The range and direction (azimuth and elevation) of the cloud is obtained by analysing the backscattered signal. A collocated CCD camera continuously monitors the change in sky conditions. Position of the scanning mirror is locked as soon as the cloud is detected. Cloud signal is compared with CCD camera image to discriminate the atmospheric water clouds. LIDAR master controller triggers IR or UV laser sources to transmit laser radiation into the specific direction for identification of cloud composition if any suspicion arises in the detected cloud signal.

3. LIDAR ACTIVITIES AT LASTEC

3.1 Backscattering LIDAR

In view of the importance of monitoring the atmosphere continuously, the authors have designed and developed a stand-alone backscattering LIDAR system, which operates at 1064 nm[9]. This system will be modified later to make it as a part of main differential absorption LIDAR (DIAL) to serve the search operation in the field in real time. The main purpose of backscattering LIDAR is to send command control to DIAL system to point in the suspected cloud direction and transmit the suitable wavelengths for identification of molecules, once they are detected in the atmosphere. The block diagram of the LIDAR system is shown in Fig. 1 and its technical specifications are presented in Table 1. This system uses a pulsed Nd:YAG laser emitting at the fundamental wavelength of 1064 nm, as the main transmitting source. Laser pulse energy is variable from 25 mJ to 400 mJ. The pulse width of the laser is 7 ns and its pulse repetition

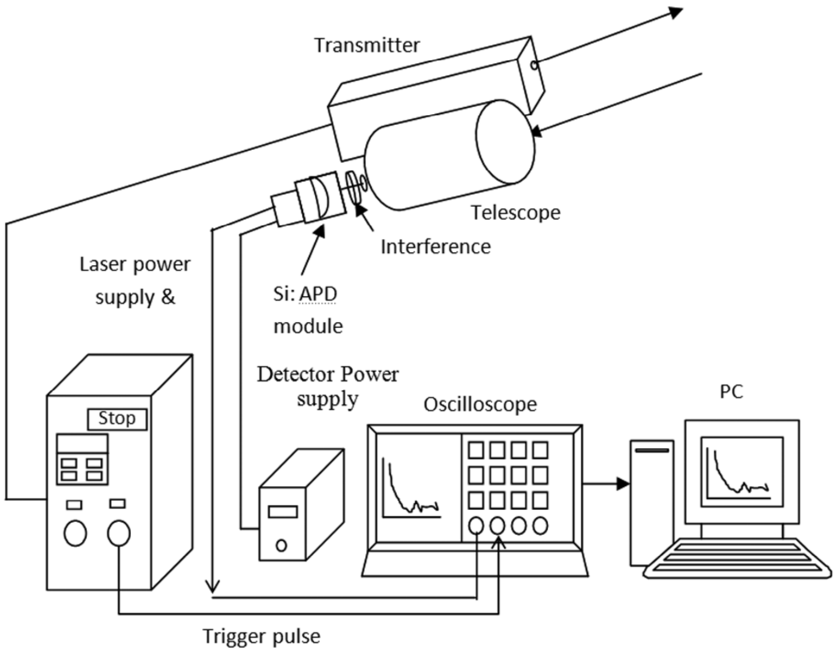


Figure 1. Block diagram of backscattering LIDAR system developed at LASTEC, Delhi.

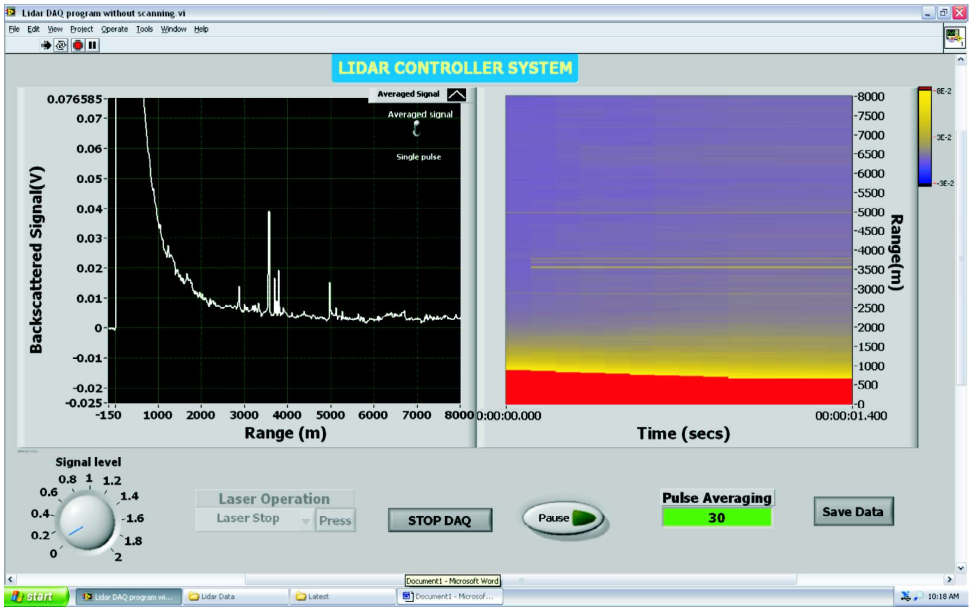
frequency is 10 Hz. The laser beam diameter 6 mm and it has a divergence of 0.6 mrad. The laser beam was transmitted into the atmosphere at an elevation angle of 12° along the slant path. The scattered radiation from the atmosphere was collected by the 200 mm diameter cassegrain telescope and its field of view was < 3 mrad. The passband interference filter with bandwidth (FWHM) of 3 nm centered on the laser wavelength was used to reduce the atmospheric background noise. Further, IR optical signal from the telescope was focused onto a high quantum efficiency Si: APD detector module (Licel, Germany). Si: APD module consists of integrated TE cooler and temperature controller, preamplifier, focusing lens and HV power supply. The weak LIDAR return echo was amplified and converted into voltage pulse for further data processing. NI's PCI bus-based DAQ card was used as data acquisition hardware in this system. First the signal from the detector was connected to analog input channel of DAQ and the trigger signal from Laser source was connected to the digital trigger input of the card. LabVIEW DAQ was configured to a sampling rate of 10MS/s to have a range resolution of 15m, which corresponds to 0.1 µs. Number of samples was set to 500 so as to collect data upto a range of 7.5 km. Panel 1 shows the LIDAR controller software developed in LabView to control the laser source and data acquisition hardware. Laser system is switched on by invoking controls in the user interface and it starts firing pulses at a rate of 10 Hz. Data acquisition process is started when start DAQ button is pressed in GUI and data for every 500 samples at 15 m range bins is stored in excel file for every laser pulse transmitted. Typical backscattered signal versus range is presented in left side of the Panel 1. The backscattered signals from the atmosphere were collected from near field to maximum range of 7-8 km. Si: APD signal reached a maximum value of about 1100 mV, which was saturation level of detector. Thereafter, the signal started falling steadily wrt range. It showed clearly the experimentally measured multiple cloud signals (cloud signal strength is higher than the background signal) at a distance of 3.5 km and 5 km. Image shown in right side of the panel 1 represents the temporal variation of the received signals. Signals received from the nearby region are very strong, and accordingly, the colour coding is assigned (red-strong signals and blue-weak signals). From the LIDAR signal, the pertinent information on the various parameters such as extinction coefficient, visibility also has been obtained using suitable LIDAR inversion methods in real time.

Table 1. Technical specifications of the backscattering LIDAR system.

Parameter	Value
Laser transmitter	
Wavelength	1064 nm
Energy	100 mJ (variable)
Pulse width	7 ns
Beam divergence	0.6 mrad
Receiver telescope	
Diameter	200 mm, Cassegrain
Interference filter	3 nm (FWHM)
FOV	< 3 mrad
Data acquisition unit	
Detector type	Si- APD module
Active diameter	3 mm
Data acquisition hardware	12 bit NI's PCI-6115 bus based card
Sampling rate	10 MS/s

3.2 Differential Absorption LIDAR (DIAL)

Differential absorption LIDAR[8] (DIAL) is the most frequently used technique employed for the detection of pollutants, toxic gases and CW agents in the atmosphere. Two laser pulses with different wavelengths are emitted into the atmosphere for detection of CW agents. One wavelength (λ) is tuned exactly to the centre of the specific absorption line of the molecule of the interest. The second wavelength (λ^{off}) is detuned to the wing of this absorption line with no specific absorption. The absorption cross-section of the molecule of interest at λ is very large as compared to that at λ^{off}. Strong return signals at both wavelengths can be detected due to large Mie scattering cross-section but the return signal at λ is weaker than that at λ^{off}. Knowledge of which wavelength has been absorbed (indicated by a highly depleted return signal as compared to that at other wavelengths) gives information about the specific constituent of the atmosphere. Ratio of the return signals at these wavelengths determines the concentration



Panel 1. LIDAR controller and data acquisition display panel. The backscattered signals shows the presence of multiple clouds at distances of 3.5–3.9 km.

of the molecules of interest due to differential absorption. Finally, the time lapsed between the transmitted laser pulse and the return pulse gives information about the distance (range) at which the cloud of this agent is located. Selecting the appropriate wavelengths for DIAL measurements involves consideration of factors such as the molecular absorption, interference from other molecular species, atmospheric transmission and scattering, laser transmitter characteristics (for example, gain factor and line width of the chosen wavelength), detector characteristics etc. The emitted laser line widths of these wavelengths should be narrower than the widths of molecular resonant transitions, which, in turn, should be less than the difference between the online wavelengths of two neighbouring species. Spectral information on online & offline absorption wavelengths and their cross-section values of potential CW agents are very much required for DIAL operation. Many of these agents have distinct absorption bands in the 3-4 µm and 9-11 µm regions[14,15], and there is relatively less atmospheric attenuation in these spectral regions. No single laser source with the required level of high peak power at each of these wavelengths is used to detect these agents in the atmosphere. CO_2 lasers (9-11 µm) have commonly been used for the detection of a majority of chemical agents[16,17]. The generation of 2-5 µm wavelengths can be done by various nonlinear techniques, like the optical parametric oscillator (OPO) technique in solid-state lasers[18,19].

3.2.1 *DIAL System Description*

OPO-based tunable mid-IR (3 – 4 µm) multi-wavelength laser source along with Nd: YAG fundamental wavelength will be used as a main transmitter in the DIAL LIDAR system. The purpose of the Nd:YAG fundamental wavelength 1064 nm is to determine the range and direction of incoming chemical clouds. This system has been developed independently and its functions discussed in Section 3.1. The design of DIAL system involves a common transmitter/receiver along with a scanning gimbal for beam delivery at the required direction and also a common command controller and data analysis systems. The laser pulse is collimated and sent into the atmosphere in the desired direction through a gimbal scanning mirror. The received signal is collected using a 500 mm diameter telescope and is focused on the detector box that contains beam splitter, intereference filters and detectors. Separate detectors are used for signals at 3-4 µm and 1.064 µm regions. Suitable interference filters permit the LIDAR signals to reach the respective detectors while blocking any stray light outside the wavelength-range of interest. The detected signals are passed through A/D converters and data processors, etc. The data processor consists of a digitiser and a computer for data storage. Block diagram of the proposed DIAL system is shown in Fig. 2. Theoretical analysis has been carried out to simulate the performance of the OPO laser-based DIAL system. For some typical parametric conditions, the required energy levels, received power levels, minimum detectable concentration and SNR of the system have been computed.

3.2.2 *Estimation of DIAL Parameters*

Let two wavelengths be considered: one corresponding to the peak of the absorption line [λ], termed as online wavelength and the other corresponding to a minimum of absorption [λ′], termed as offline wavelength. The LIDAR equation[8] for these two wavelengths from the distance, R:

$$P(\lambda,R) = P_t\left(\frac{c\tau}{2}\right)\beta(\lambda,R)\xi(\lambda)\xi(R)\frac{A}{R^2}.\exp\left[-2\int_0^R(\alpha+N\sigma)dR\right] \tag{1}$$

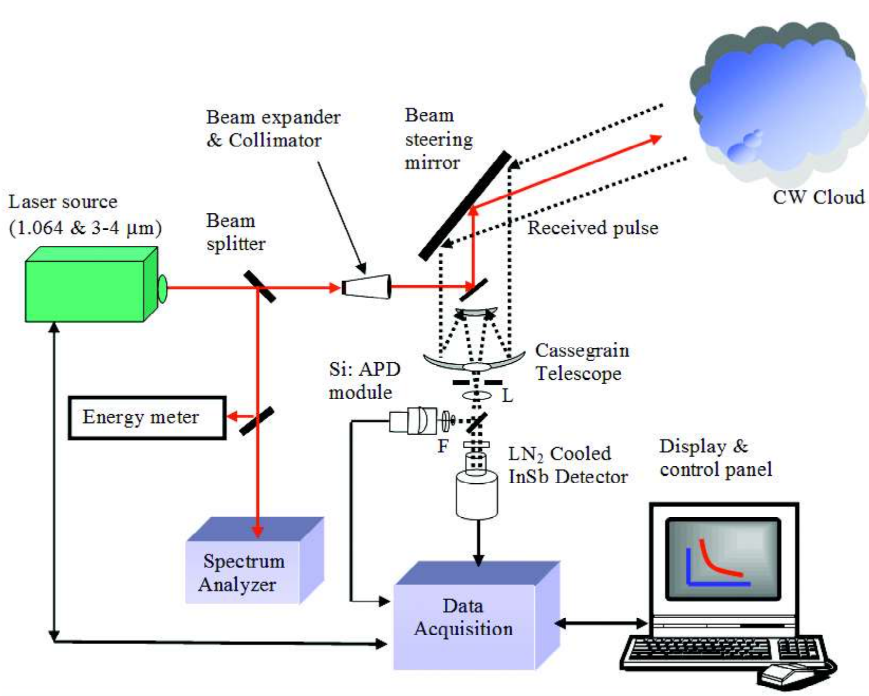


Figure 2. Schematic diagram of differential absorption LIDAR (DIAL) system.

$$P'(\lambda',R) = P_t'\left(\frac{c\tau}{2}\right)\beta'(\lambda',R)\xi(\lambda')\xi(R)\frac{A}{R^2}.\exp\left[-2\int_0^R(\alpha'+N\sigma')dR\right] \tag{2}$$

where c is the velocity of the light, $\beta(\lambda,R)$ is the volume backscattering coefficient of the atmosphere, $\xi(\lambda)$ is the receiver's spectral transmission factor which includes the influence of any other elements such as monochromator, $\xi(R)$ is the probability of return pulse reaching the detector from a distance R, A is the effective receiver area, α is the extinction/attenuation coefficient of the atmosphere due to scattering from aerosols and absorption by molecules other than the toxic agent, and σN is the contribution from the absorbing toxic agent (σ is the absorption cross-section and N is the number density of that agent). P_t and P_t' are the laser transmitted powers at λ and λ' respectively.

In general, the ratio of two return signals is used to derive the number concentration of the chosen chemical agent. If measurements at λ and λ' are made near-simultaneously, one can assume $\xi'(\lambda') \cong \xi(\lambda)$, $\beta \cong \beta'$ and $\alpha \cong \alpha'$. Following is the range-resolved expression for the retrieval of number concentration N (m^{-3}) of the CW agent:

$$N = \frac{1}{2(\Delta\sigma)}\frac{d}{dR}\left\{\ln\left(\frac{P'}{P}\right)\right\} \tag{3}$$

where $\Delta\sigma$ is the differential absorption coefficient, dR is the range resolution, P is the online signal strength and P' is the offline signal strength.

The noise contributions arise mainly from the combined effects of detector dark noise and the received background radiation. In the mid-IR range (spectral range of our interest), both the solar and terrestrial thermal radiation contributions are very small and hence can be neglected. While the dark noise is negligible for good detectors in the visible and near IR, the detectors in the mid-IR have fairly large dark noise. Since the origin of this dark noise is thermal in nature, cooling the detector to liquid N_2 temperature (77 K) reduces the dark noise contributions significantly. It should be noted[20] that the detector noise in the case of heterodyne (coherent) LIDAR with sufficient local oscillator power is shot-noise limited (noise value ≅ 10^{-12} W), for direct (non-coherent) LIDAR system with weak return signals it is dark-current limited in the mid-IR spectral region. Note that the SNR is now range-dependent and, for the case of thermal-background limited case, the SNR of solid-state detector is given by

$$SNR = \sqrt{n}\frac{P}{NEP} \tag{4}$$

where P is the received power, NEP is the noise equivalent power of the detector and n is the number of received pulses. In the dark-current limited case, NEP of the detector is given by

$$NEP = \frac{\sqrt{A_d B}}{D} \tag{5}$$

where D^* is the detectivity, A_d is the area of the detector, and B is the detection bandwidth. The sensitivity of the DIAL method is characterised by the minimum concentration N_{min} of the CW agent that can be detected with the minimum errors in optical signal. The expression for the minimum detectable concentration of toxic agent is given below under the condition of the backscattering and extinction coefficient is negligible at nearby wavelengths of λ and λ^{off}. For the return signals P and P′ to be distinguishable from each other, it is essential that they satisfy the following criterion for the given detector:

$$\Delta P = P' - P \geq NEP \tag{6}$$

From Eqn (4), for n=1, one gets

$$NEP = \frac{P}{SNR} \tag{7}$$

From Eqns (3) & (6)-(7), for a given range resolution ΔR, one gets

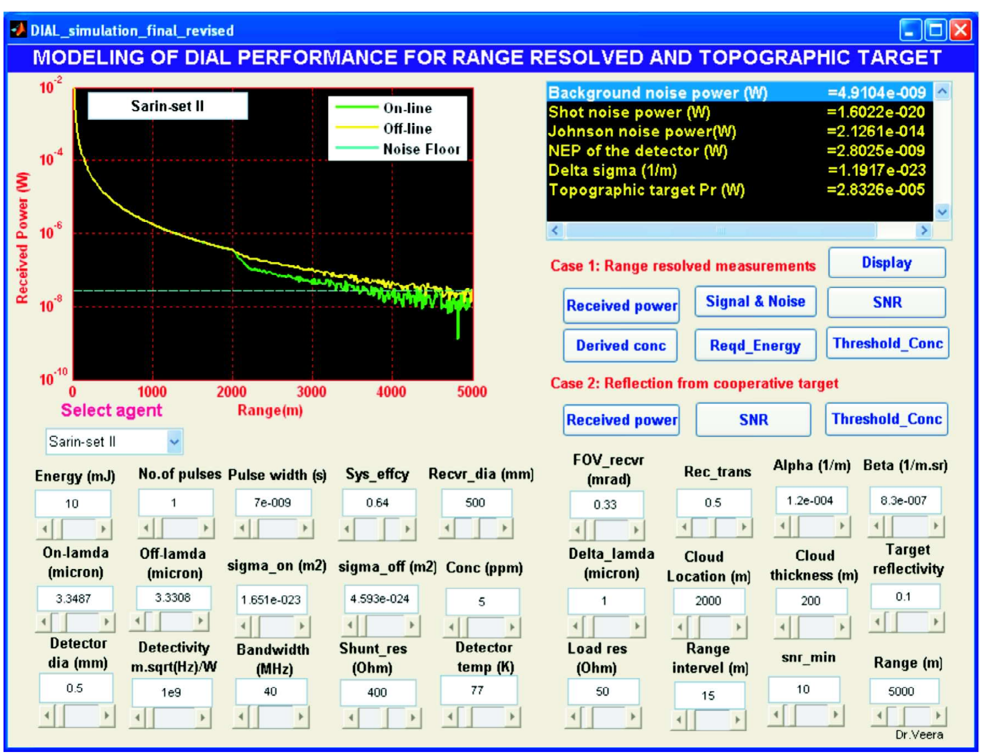
$$N \geq \frac{1}{2(\Delta\sigma)(\Delta R)}\ln\left(1+\frac{1}{SNR}\right) \tag{8}$$

From this, one gets an expression for the minimum detectable concentration (N_{min}) as

$$N_{min} = \frac{1}{2(\Delta\sigma)(\Delta R)}\ln\left(1+\frac{1}{SNR_{min}}\right) \tag{9}$$

where SNR is the signal-to-noise ration at the distance R. To increase the sensitivity at the given spatial resolution (ΔR), the most intense absorption lines of the gas under study with large absorption cross-section is to be selected. Given typical detection and digitisation equipment, a minimum reasonable value for SNR is 10.

Using above equations, one can now proceed to compute values of various parameters such as received powers, signal-to-noise ratio, and minimum detectable concentration etc. of the muliwavelength DIAL system for the detection of CW agents. The system capability is evaluated for two cases namely: (1) range-resolved measurements (mainly from the aerosol scattering), (2) cooperative target (reflected signal from topographic target). A chemical cloud with a thickness of 200 m containing uniformly distributed concentration of 5 ppm to be detected in the ambient atmospheric conditions over distances from 0 m to 5 km is assumed. Aerosol concentration in the atmosphere is taken to be uniform. For the sake of simplicity, the effect of wind velocity on the concentration levels and the dispersion of toxic-agent cloud have not been considered. It is also assumed that the atmosphere is clear, i.e., neither clouds nor fog is present. Further, the authors have taken the values for $\xi(\lambda) = 0.8 = \xi(R)$ in their calculations. DIAL simulation model has been developed for this system performance analysis studies. It takes various inputs from the user such as spectral data of absorbing agents, important parameters of laser transmitter, receiver system, detector electronics parameters and computes the expected return power levels, SNR, required transmitter energy etc. at various ranges. A graphical user interface (GUI) software has been developed in MATLAB platform to perform the simulation studies and it is shown in panel 2. IR absorption lines of the potential CW agents are generated and incorporated in the GUI. As an example, the return signal strength versus range obtained for online and offline wavelengths for sarin is shown here. The return signals are simulated according to Eqns (1) and (2) taking into account detector gain, responsivity, background and detector noise sources and other system parameters shown in panel 2. The strong depletion of signal level is seen at online wavelength between 2 km and 2.2 km, this signal falls uniformly with range and reaches below the noise floor after 4.5 km. Any discernible detection requires the LIDAR signal to exceed the NEP by an adequate margin. Here, the noise floor of the system is 10 times of the NEP of InSb detector. The maximum detectable range of the system is defined as the range at which the return signal strength of CW cloud is totally above the noise floor. The maximum detectable range for this case is 3.2 km. After 3.2 km, the return signal falls totally below the noise floor which means this system cannot detect CW cloud if it is present beyond 3.2 km. Hence, it can be said that this system can detect the nerve agent cloud (sarin) of thickness 200 m with 5 ppm concentration up to a range of 3.2 km. Under cooperative target, this system can detect nerve agent cloud up to a maximum range of 7 km. In this case, the location of the cloud may not be known because it provides path integrated concentration of a given species only. It may be noted that a strategically located retro-reflector increases range and sensitivity, whereas range-resolvable measurements are leading to spatial mapping of chemical clouds over a long range. The sensitivity of



Panel 2. Graphical user display panel developed for DIAL system modelling.

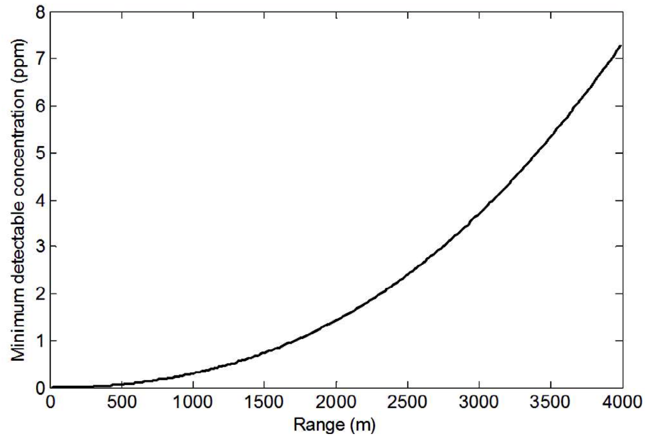


Figure 3. Minimum detectable concentration versus range computed for tabun agent using DIAL technique.

the system in terms of minimum measurable concentration is computed for tabun agent and shown in Fig. 3. At shorter ranges (below 1 km), sensitivity of the system is less than ppm level whereas this increases beyond 1 km. In any case, the minimum detectable concentration is inversely proportional to the range resolution and differential absorption of cross-section which depends on the choice of the wavelengths of the probe radiation.

3.3 Laser induced fluorescence LIDAR System

Laser induced fluorescence (LIF) is the emission from atoms or molecules that have been excited to higher energy levels by absorption of laser radiation. When excited with a laser, the excited atoms or molecules will after some time, usually in the order of few ns to ms, de-excite and emit light at a wavelength larger than the excitation wavelength. The stand-off detection of BW agents is based on this concept. In general, most of the biological warfare (BW) molecules fluoresce when they are excited by a suitable wavelength. These BW molecules are mostly constituted by aromatic amino acids and coenzymes. Aromatic amino acids, such as tryptophan, tyrosine and phenylanine absorb light at 280-290 nm and they fluoresce in the spectral band[11] between 300 nm and 400 nm. Biogenic chemicals associated with cell metabolism, such as reduced nicotinamide adenine dinucleotide (NADH) and riboflavin have their maximum absorption cross-section at around 340 nm and the resulting fluorescence peaks between 450 nm and 560 nm. Hence, it is possible to detect the BW agents using suitable UV excitation wavelength. Also, the discrimination of biological agents can be achieved only from the LIF signal because the fluorescence cross-sections for particles 1-10 μ size range are sufficiently large to make single particle interrogation feasible. Currently, most prototype LIF LIDAR[21-23] use either 266 nm or 355 nm UV light; both these wavelengths being easily derived from an Nd:YAG laser, which has a small footprint, relatively low maintenance and is readily available as a commercial source. 266 nm UV excites fluorescence primarily from the tryptophan within the bacterial cell wall and tyrosine (also NADH and flavins found in abundance in growth medium) and 355 nm UV excites fluorescence primarily from NADH (and also flavins) but not tryptophan. Therefore, it could be argued that 266 nm light detects proteins present in the bacterial cell wall whereas 355nm light detects compounds found in large quantities in a growth medium and which are less abundant in bacteria. However, the attenuation of 266 nm light by atmospheric ozone is approximately 10-times greater than that of 355 nm and so 355 nm LIDAR systems may have a longer detection range.

The principal components of typical UV LIF LIDAR are an ultraviolet laser, a telescope, two photomultiplier tubes: for recording the scattered signal and temporal fluorescence signal, a spectrograph with a gated-intensified CCD (ICCD) array for recording the dispersed fluorescence spectra, and the necessary data acquisition unit and LIDAR control electronics. The fourth harmonic output from Nd: YAG laser is transmitted towards the BW cloud region. A 300 mm Cassegrain telescope collects the backscattered and biofluorescence signal from the target area. Gated PMT channel receives the backscattered elastic scattering signal from the atmosphere with respect to time. The sudden enhancement in the backscattered signal would be seen if there is any cloud present along the beam path. The distance of the cloud will be determined from this channel. Solar blind PMT channel will be opened only if there is any suspicious cloud which gives the total fluorescence signal. Spectrograph with a gated ICCD is used to identify the nature of the biomolecule which is responsible for the fluorescence. FOV of the receiver is kept smaller so as to reduce the unwanted background radiation. The block diagram of a typical monostatic UV-LIF LIDAR used for

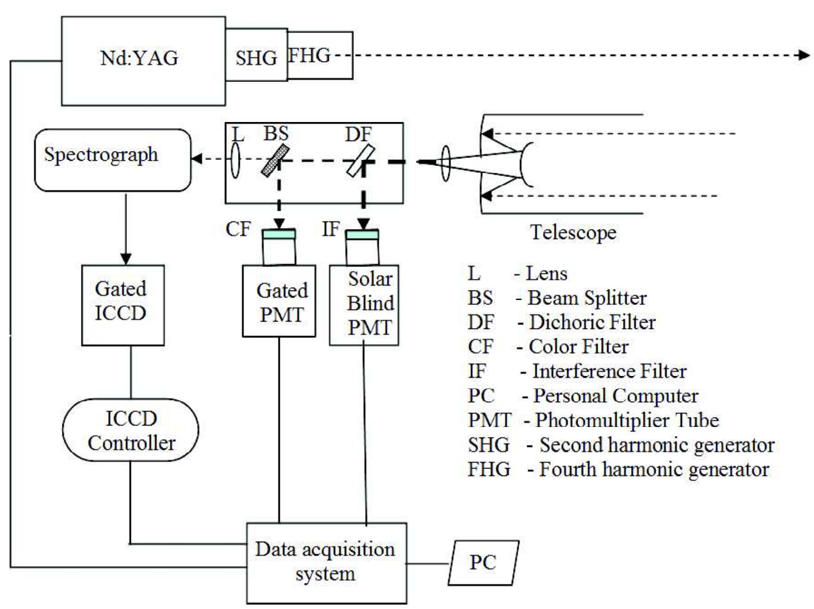


Figure 4. Block diagram of the UV LIF LIDAR system.

detection of biological warfare agents is shown in the Fig. 4. Theoretical studies have been carried out to simulate the system performance under given parametric conditions. A simulation model has been developed in MATLAB for these studies. It takes various inputs from the user such as spectral data of BW agent, important parameters of laser transmitter, receiver, detector electronics parameters and computes the expected return power levels, total fluorescence, SNR, minimum detectable concentration etc. at various ranges.

3.3.1 Estimation of LIF LIDAR System Parameters

A simulation of UV LIDAR depicting the received fluorescence signal as a function of range is performed for the given system specifications shown in Panel 2. The return signal at a range r is given by the fluorescence LIDAR equation in terms of photon counting[23]:

$$N_s = \frac{E_t\lambda}{hc}\frac{A}{r^2}\eta(\Delta R)(N_{bio}\sigma_{bio})e^{-\int_0^r \alpha_a dr}e^{-\int_{R_1}^{R_2}\alpha_F dr} \quad (10)$$

where N_s is the return signal in photon counts, E_t is the laser pulse energy (mJ), h is the Planck's constant, c is the velocity of light (m/s), λ is the laser wavelength (nm), N_{bio} is the biological agent concentration (ppl), σ_{bio} is the fluorescence cross section of biological agents (m^2), A is the telescope area (m^2), η is the overall receiver efficiency, ΔR is the range resolution (m), R_1 and R_2 is the BW cloud's start and end range, and α_a, α_F is the atmospheric attenuation coefficient at the laser and fluorescence wavelengths (m^{-1}).

Signal-to-noise ratio of the system for single pulse operation is given below:

$$SNR_{single} = \frac{N_s}{\sqrt{N_s + N_b + N_d + N_{ampl}}} \quad (11)$$

where, N_{ampl} is the Johnson amplifier noise, N_d is the dark noise, N_b is the background noise. Adequate performance of the system requires $SNR_{min} \geq 20$. Averaging of multiple pulses is required to achieve this level. Assuming, one integrates over 1000 pulses, the required single pulse SNR would then be

$$SNR_{single}^{reqd} = \frac{snr_{min}}{\sqrt{N}} = 0.632 \quad (12)$$

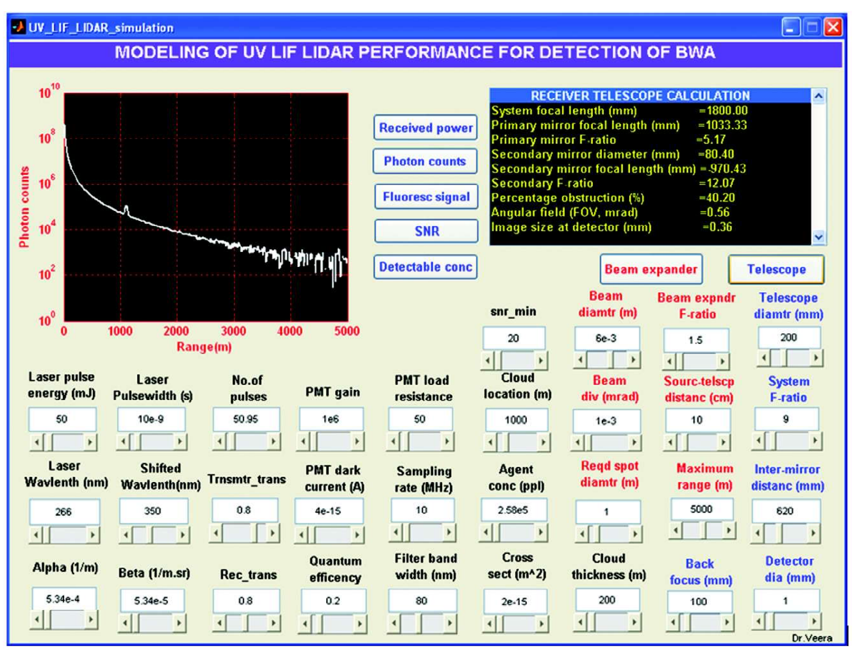
The required minimum detectable photons per pulse are computed using Eqn (13) as

$$0.632 = \frac{N_s^{min}}{\sqrt{N_s^{min} + N_b + N_d + N_{ampl}}} \quad (13)$$

The values of N_b, N_d, and N_{ampl} are computed as per the system specifications shown in Panel 2 and used in the above equation to get the minimum detectable photons. Once the minimum detectable photons per pulse is known, one can calculate the minimum detectable concentration of bioaerosols, n_a^{min} (particles/m^3) as a function of range, which is given below:

$$n_a^{min} = \frac{N_s hcr^2 e^{\int_0^r \alpha_a dr} e^{\int_{R_1}^{R_2}\alpha_F dr}}{E_t\lambda A(\Delta R)\eta\sigma_{bio}} \quad (14)$$

Using above equations, the values of various parameters of the UV LIF system have been computed for the detection of biological aerosols. Bacterial spores, *Bacillus globijii* (simulant of bacillus anthracis) of typical size 1 μm was considered in the calculation. These spores fluoresce at 350 nm when it is excited by 266 nm laser radiation. The fluorescence cross-section[24] of these bacterial spores at the fluorescing wavelength band is 2×10^{-11} cm^2/particles. The range profile of a simulated monodisperse of *Bacillus globijii* (BG) cloud of 200 m width at 1000 km range and peak concentration of 2.58×10^5 particles per litre is assumed in the calculation, although the software program is general in nature and can cater to different values equally well. Aerosol concentration in the atmosphere is taken to be uniform. Further, the values for overall system efficiency (η) = 0.12 was taken in the calculations (η=quantum efficiency×transmitter efficiency×receiver efficiency). Based on the assumed BG concentration distribution, range dependent elastic backscattered signals at excitation wavelength 266 nm in terms of photon counts are simulated using the system parameters shown in panel 3. The laser parameters like E_t=50mJ, τ=10ns, prf=20Hz and A=0.0314 m^2 (collection area of telescope) were used in the calculation to simulate



Panel 3. Graphical user interface display panel developed for LIF LIDAR system modelling.

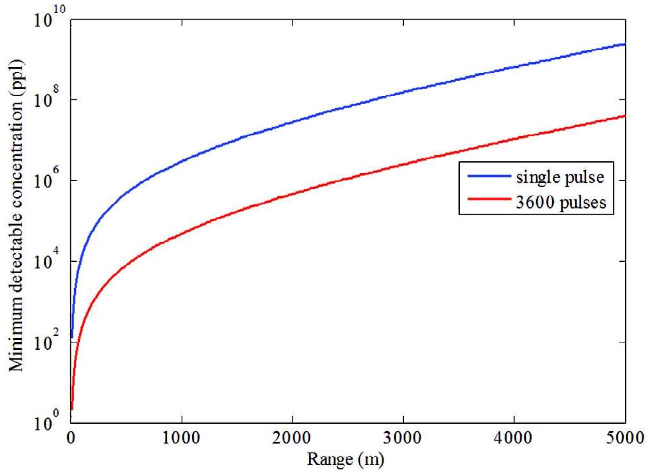


Figure 5. The minimum detectable concentration versus range computed for fluorescence LIDAR for transmission of single pulse and the average of 3600 pulses.

the received photon counts. Top left corner figure of panel 3 describes the backscattered signal versus range obtained from the atmosphere. The backscattered signals exhibit a peak between 1.0 and 1.2 km, indicating the presence of a cloud at that range. The white Gaussian noise was also introduced in the simulated signal. Fluctuations of return signal is very high at the longer ranges, which means that the system cannot discriminate the cloud signal from the background noise level. The analysis revealed that this system can detect the presence of BG cloud with 200 m thickness and the concentration of 2.58×10^5 ppl maximum upto 2.5 km only. The sensitivity of the system in terms of minimum detectable concentration wrt number of transmitted laser pulses was also estimated. The minimum detectable BG concentration in ppl versus range for signal-to-noise-ratio (SNR) of 20 for transmission of single laser pulse and average of 1000 pulses were calculated and presented in Fig. 5. It is assumed that the averaging of multiple laser pulses improves the SNR by a factor equal to the square root of the number of pulses, and hence, the sensitivity of the system increases significantly. The averaging of 3600 pulses (equal to the detection time of 3 min) resulted the fluorescence detection range of 560m for a lethal infective dose of ~10,000 ppl. Prior to the cloud dispersing to that concentration, it will have higher values. At 2000 m, it can detect the minimum concentration of 8.75×10^5 ppl. The error in the fluorescence cross-section values is expected to affect largely the determination of minimum detectable concentration.

4. CONCLUSIONS

The types of LIDAR systems for detection of chemical and biological warfare agents in the atmosphere have been presented. Detection approach for locating the few hundred meter thickness chemical or biological cloud is also discussed. The backscattering LIDAR operating at 1064 nm has been designed and developed at LASTEC keeping in view the importance of monitoring the atmosphere continuously for detection of incoming clouds. This system uses 100 mJ laser source as a transmitter and 200 mm dia Cassegrain telescope along with Si: APD detector module as a receiver. One of the experimental data taken on the intermittent rainy day showed the clouds at distances of 3.5 km and 5 km. Also, the results of the theoretical estimation of DIAL system parameters such as receiver power levels, SNR, etc, have been presented and discussed. It is found that 10 mJ OPO laser-based DIAL system possess the capability of detecting CW clouds of few hundred meter width with 5 ppm concentration up to a range of 2 km based on aerosol scattering and molecular absorption. However, this system can detect theses clouds maximum up to 7 km in the presence of the cooperative target. The sensitivity of the system in terms of minimum measurable concentration revealed that at shorter ranges (below 1 km), sensitivity is less than ppm level. Similarly, the parametric studies of UV LIF LIDAR are also discussed. The system operating at 266 nm wavelength with 50 mJ pulse energy and 300 mm dia receiver telescope can detect the BG cloud with the concentration of 2.58×10^5 ppl maximum up to 2.5 km. The pulse averaging of 3600 pulses (equal to the detection time of 3 min) resulted the fluorescence detection range of 560 m for a lethal infective dose of ~10,000 ppl.

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