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Lidar and Dial application for detection and identification: a proposal to improve safety and security

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Abstract: Nowadays the intentional diffusion in air (both in open and confined environments) of chemical contaminants is a dramatic source of risk for the public health worldwide. The needs of a high-tech networks composed by software, diagnostics, decision support systems and cyber security tools are urging all the stakeholders (military, public, research & academic entities) to create innovative solutions to face this problem and improve both safety and security. The Quantum Electronics and Plasma Physics (QEP) Research Group of the University of Rome Tor Vergata is working since the 1960s on the development of laser-based technologies for the stand-off detection of contaminants in the air. Up to now, four demonstrators have been developed (two LIDAR-based and two DIAL-based) and have been used in experimental campaigns during all 2015. These systems and technologies can be used together to create an innovative solution to the problem of public safety and security: the creation of a network composed by detection systems: A low cost LIDAR based system has been tested in an urban area to detect pollutants coming from urban traffic, in this paper the authors show the results obtained in the city of Crotone (south of Italy). This system can be used as a first alarm and can be coupled with an identification system to investigate the nature of the threat. A laboratory dial based system has been used in order to create a database of absorption spectra of chemical substances that could be release in atmosphere, these spectra can be considered as the fingerprints of the substances that have to be identified. In order to create

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the database absorption measurements in cell, at different conditions, are in progress and the first results are presented in this paper.

Keywords: Detector alignment and calibration methods (lasers, sources, particle-beams); Lasers; Data acquisition concepts; Detector design and construction technologies and materials

Contents

1 Introduction

Nowadays, the Chemical-Biological-Radiological-Nuclear-explosive (CBRNe) risk is one of the world's large safety concern. The radiological disasters of Fukushima and Chernobyl, the chemical events of Seveso or the release of Sarin in the Tokyo subway, the biological emergencies such as the H1N1 flu or the recent Ebola outbreak, as well as the possible availability of non-conventional weapons acquired by fundamentalist organisations, represent evidences of potential future concern [1].

The voluntary release of toxic gases in the past and in the recent history [2–4], as well as the risk of toxin dispersion in water and the DAESH progression in the Arabic Countries [5–7] are all examples of how the combination of well-known threats and with new "dangerous ideas" has exponentially increased the uncertainties for the human safety all around the world. At the same time, the risk of dispersion of dangerous chemical agents in atmosphere or in confined environments is a matter of fact. The intentional release of CWA (Chemical Warfare Agents) with the purpose of creating terror, or the emission in the environment of TIC (Toxic Industrial Chemicals) or TIM (Toxic Industrial Materials) both from industrial and civil applications is a problem that has to be faced with innovative solutions to improve the emergency system (see figure 1):

Figure 1. Emergency system in case of a CBRNe release [8].

The Quantum Electronics and Plasma Physics (QEP) Research Group of the University of Rome Tor Vergata has focused its attention on the development of a laser system for the detection and identification of chemicals in air, the so called "detection phase" (figure 1). Currently several products to detect and identify the Chemical Agents (CA), the CWA and TIC/TIM are commercialized, however they can be only used in the range of few meters. A detailed presentation of the products available on the market, for the CA detection and identification, is reported in [9] and [10]. The capability to detect and identify through the use of optical techniques can be find in [11] and [12]

It can be used only to detect any putative variation of the chemical background in a confined area, providing an on/off response type. In this article, the authors demonstrate the capabilities of a developed quasi real time tool for detection and/or identification of CAs. The developed systems are:

- Laser systems based on the LIDAR techniques for the detection of chemicals dispersions;
- Laser systems based on the DIAL techniques for the identification of chemicals dispersions.

2 Materials and methods

2.1 LIDAR unit

The compact ground-based mini LIDAR (figure 2) station — COLI has been built by the QEP research group and continuously upgraded at the CRATI s.c.r.l. c/o University of Calabria.

Figure 2. COLI experimental set-up during the experimental campaign of Crotone, February 2015. In the figure the laser source and the receiver are at the same location and the system is biaxial.

A commercial and relatively standard pulsed Nd:YAG Laser in Q-switching mode was used as the transmitter, providing 8ns width pulses with a maximum repetition rate of 20 Hz at 1064 nm.

The receiver system is composed of a silicon avalanche photodiode (with a quantum efficiency equal to 38%) connected to a telescope, based on the Cassegrain configuration. Data acquisition was performed using a NI-PXI with 14-bit resolution at 100 MS/s (200 MHz) sampling rate. These digitization parameters yield a range resolution of 1.5m and a maximum theoretical detection range of 1.5 km. The entire apparatus stands on a mobile system and therefore constitutes a mobile station, which can be used either on the field or in any other location. COLI is remotely controlled by our own software package, written in LabVIEW and Matlab, explicitly developed for this application. The QEP Research Group has a long experience in LIDAR system development and its applications [12–21].

The COLI acquisition system is able to elaborated the backscattering signals on the well know elastic LIDAR equation (2.1) [22]:

$$P_r(\lambda, R) = E_1 \frac{c}{2} \frac{A_r}{R^2} \beta(\lambda, R) C(\lambda, R) \exp\left(-2 \int_0^R K(\lambda, R') dR'\right). \tag{2.1}$$

Lidar equation is the way to relate the light power backscattered by the atmospheric target with the signal collected by the LIDAR receiver. Where: $P_r(\lambda, R)$ is the backscattered power received from the distance R, at the specific laser operative wavelength λ (because the equation describe the elastic scattering), E_1 is the laser pulse energy, c is the speed of light, the term $A_r \cdot R^{-2}$ is the acceptance solid angle of the receiver optics with collecting area A_r, $C(\lambda, R)$ is a function determined by the geometric considerations of the receiver optics, the transmitter (set at 100%) and receiver efficiencies, and the overlap of the emitted laser beam with the field of view of the receiver. The last two terms are known as the optical parameters and are closely linked to the aerosols load: the backscattering coefficient $\beta(\lambda, R)$ is a measure of the scattering in the backward direction (i.e. towards the incident direction, at a scattering angle of 180°) for the light encountering the atmospheric aerosol particles and molecules. Instead, the extinction coefficient $K(\lambda, R)$ is a measure of attenuation of the light passing through the atmosphere due to the scattering and absorption by aerosol particles and molecules. Since it is reasonable to assume that molecular backscattering is negligible in the infrared region, and that particulate backscattering dominates in this region, the LIDAR signal gives particle backscatter information directly if laser is operating in this region. By assuming a relationship between relative variation of backscattering coefficient and particulate mass or number density, the LIDAR signal can be used to monitor and track atmospheric particles.

From relation (2.1), and thanks to the Klett inversion method [23–25], it is possible to extract both the extinction and the backscattering coefficient. In this paper, the attention is focused on the particle backscattering coefficient, the primary atmospheric parameter that determines the strength of the LIDAR signal. The far boundary solution is reported into equation (2.2):

$$\beta(R, \lambda) = \frac{e^{[\mu(R,\lambda) - \mu_m(\lambda)]}}{\frac{1}{\beta_m(\lambda)} + \frac{2}{P_\pi(R,\lambda)} \int_R^{R_m} e^{[\mu(R',\lambda) - \mu_m(\lambda)]} dR'}. \tag{2.2}$$

Where: $\mu(R, \lambda)$ is the Range Corrected Signal (RCS), $\mu_m(\lambda)$ is the RCS calculated at the far boundary of the LIDAR range R_m, P_π is the phase function and $\beta_m(\lambda)$ is the integration constant.

Furthermore, since the LIDAR signal is affected by a background noise due to the electronics, the Signal-to-Noise Ratio (SNR) has been calculated to evaluate both the accuracy of measurements and the far range boundary point for the Klett solution. In fact, SNR is useful to determine the farthest point, above a certain threshold (e.g. SNR = 1), that LIDAR can reach to detect a small smoke plume without loss of accuracy.

Finally, the output laser energy has been reduced to take into account the eye-safe limits, imposed by MPE (Maximum Possible Exposure) standards.

2.1.1 Experimental results

Thanks to the COLI system, it is possible to detect anomalies in terms of variation of the normal backscattered LIDAR signal sent in atmosphere through the application of equations (2.1) and (2.2). These variations can be resolved both in time (figure 3) or space (figure 4) and visualized through backscattering coefficient maps that are essentially to give the exact time and position of the detected anomaly. Nonetheless the maximum range reached by COLI system is equal to 1.5 km, it is quite common, for reasons of safety and due to the constraints of the experimental field/investigated area, to reduce the far range boundary point of LIDAR system. For these reasons, the two backscattering maps reported in the following figures have been cut from zero to 500–600 m. In spite of these limitations, this improves the accuracy of experimental results, increasing the SNR level.

Figure 3 show the COLI signal's map resolved in time. Results are referred to the experimental campaign carried out at Crotone during February 2015. As shown on the right side of figure, COLI has been placed into the courtyard of a school pointing in direction 351° from the North with an elevation angle of 0.8°. In order to monitor the atmospheric pollution due to local vehicular traffic, the Line of Sight (LOS) has been horizontally fixed along a traffic congested road in the suburban area. The experimental set-up guaranteed the safety of both operators and pedestrians/drivers. The data collected in situ have been acquired and quasi real-time processed by a remote workstation with a temporal resolution of 10ns and a range resolution of 1.5 m. The white box on the left side of the figure highlights an increase of backscattering level strictly related to a real traffic jam detected

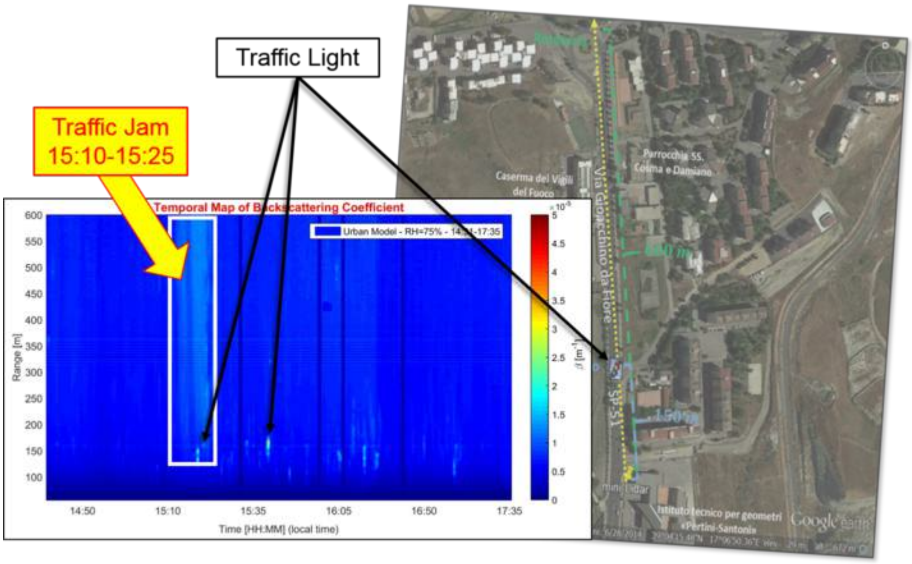

Figure 3. COLI signal's maps resolved in time.

in the afternoon of February 11, 2015. Erroneous measurements have been discarded and depicted with dark blue intervals. Moreover, some obstacles have been revealed by LIDAR, such as the traffic light placed at 150 m from the system's position. (These misestimating of β could be probably due to a temporary and unexpected oscillation of the laser-telescope block caused by the *wind*).

In the following figure 4 the COLI signal's maps resolved in space and time is showed. The experimental campaign has taken place in the Industrial area in south of Italy. A controlled fire, produced by the combustion of a known quantity of vegetables has been lighted into a chimney at a distance of about 400 m from COLI (both COLI and chimney positions are marked with different colours). To observe two-dimensional temporal and spatial distribution of smoke particles, horizontal scans were executed. The elevation angle was set to zero and the azimuth angle was changed in 1.234° steps in counter clockwise direction from 270° to 263.83°, covering a range of 6.2°. At each step, 100 laser shot were averaged and each scan took approximately 1 min to complete. The scans (A) and (B) were respectively performed between 10:08–10:09 and 11:19–11:20 on 11 June 2014. Each scan has been reported in both Cartesian (left side) and polar (right side) diagram. The red dotted boxes highlight the increase of backscattering level linked to the smoke fluctuations. It is possible to notice that red spots rapidly change their position from the source of smoke even hundreds of meters. This was due to the presence of wind blowing from the North (A) and West (B).

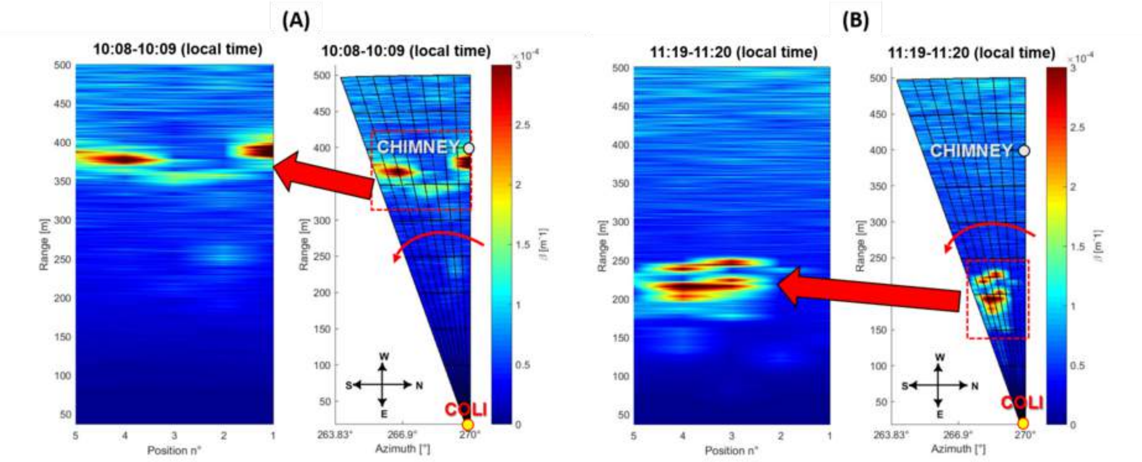

Figure 4. COLI signal's maps resolved in space and time.

2.2 Absorption measurements in cell

From the results presented in section 2, the LIDAR techniques can be used only to provide an alarm. In case of chemical events, it is essential to deploy also systems able to identify the chemical substances released. For this reason, the QEP research group are developing a Mini-Dial system multi-wavelengths based named TELEMACO. The Dial technology usually employs two different wavelengths in order to measure the concentration profiles of an investigated molecule. In the case of organic substance unfortunately the absorption spectra show different overlaps causing interference phenomena that do not allow the recognition using the classical dial methodologies based only couples of laser lines [26]. The dial multi-wavelengths methodologies, instead could be applied in order to identify the organic compounds using backscattering signals from different wavelengths. Consequently, a *fingerprint* database is required, composed by a collection of absorption coefficients to identify molecules and to minimize the risk of wrong detections or false alarms. Actually, data mining techniques have been developed to analyse the database of fingerprints in order to selected, for every organic compound, the minimum number of laser lines essential to identify the gas minimizing false alarm conditions.

Nowadays there is not such a collection of data in the scientific and technical literature. Furthermore, the exactly value of absorption coefficients is influenced by the type of light source adopted. The mini TEA CO_2 laser is adopted for TELEMACO for absorption coefficient measurements made with cells filled with the investigated molecules. We got, through this method, a preliminary results of proper fingerprint database, necessary for future application in atmosphere in order to identify dangerous molecules. The CO_2 laser has been chosen because it is eye safe and, because it covers a spectral band where there is good absorption for this kind of molecules. This work started with the TAEMS [27–30] systems where preliminary fingerprints of mustard gas was measured [27] and it is going on nowadays with the TELEMACO system.

The performance of the TEA CO_2 laser is listed in table 1:

Table 1. TEA CO2 Laser.

Output power	10^9 W
Beam divergence	0.77 mrad
Spectral range	9:11 μm
Receiver	
Primary ROC	1300 mm
Primary diameter	200 mm
ZnSe focal length	7 mm
F.O.V.	0.88 mrad
Detector type	HgCdTe
Detector Sensitivity D*	$3.38 \cdot 10^{10}$ cm $Hz^{1/2}$/W
Detector size	1 mm^2

The preliminary measurements are carried out in laboratory in order to evaluate the different spectrum of several aggressive chemical compounds. A description of absorption layout assembled in laboratory for in cell measurements using the same laser of TELEMACO is described in figure 5.

The absorption setup is based on a TEA CO_2 laser tuneable over 60 wavelengths, from 9 to 11 μm, and it has been fully equipped with an electronic micrometre to automatically rotate the diffraction reticule and change the wavelengths. This laser has been chosen because most of the CA have the maximum and minimum value of its absorption spectra in this range of between 9–11 μm.

The absorption coefficient $\alpha(\lambda_i)$ for the λ_i is calculated by the ratio between the transmitted beam energy and the measured one by the sensor number 2 (Transmitted intensity — I_T) and by the sensor number 1 (Incident intensity — I_0). Indicating with β the reflectance of the beam splitter,

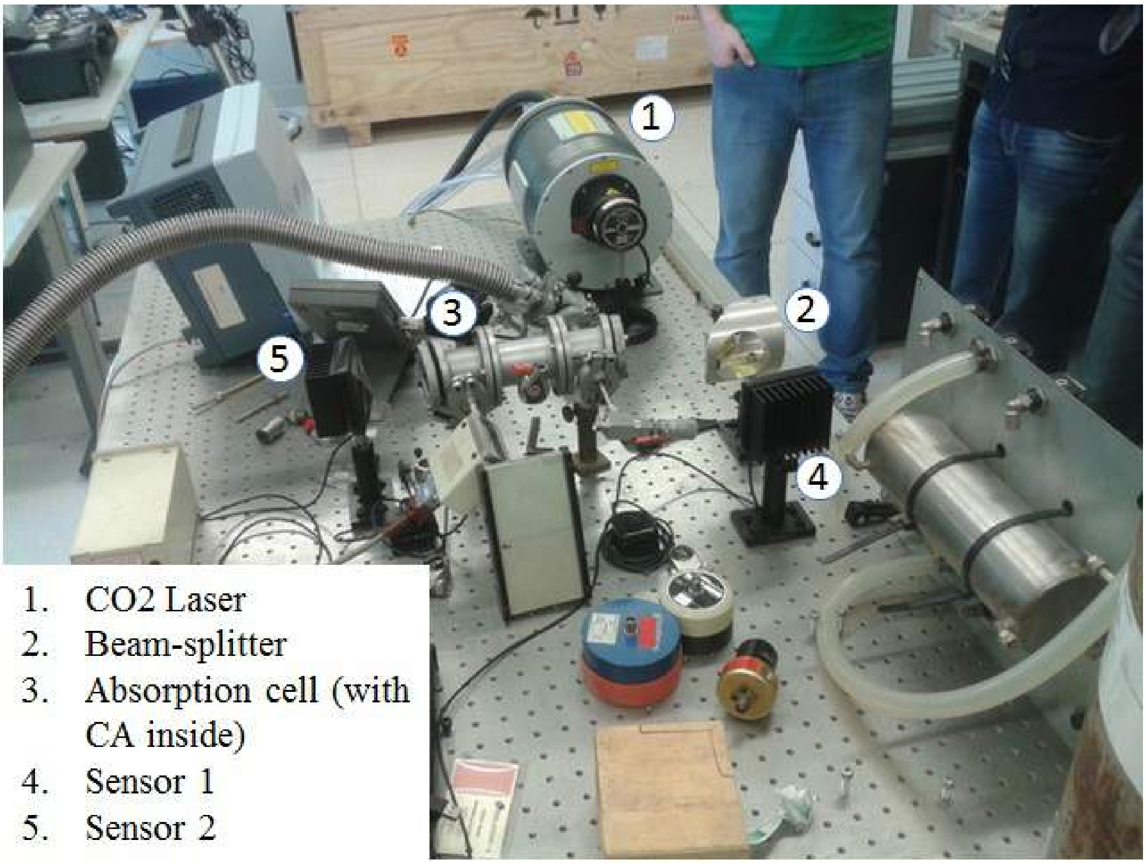

Figure 5. Absorption laboratory layout based of the same CO2 laser of TELEMACO system.

the equations (2.3), (2.4) and (2.5) relate the three intensities:

$$I_1 = \beta \cdot \tag{2.3}$$

$$I_0 = (1 - \beta) \cdot I \tag{2.4}$$

$$I_T = I_0 A_f A_g = (1 - \beta) \cdot I \cdot A_f A_g. \tag{2.5}$$

Where I is the intensity of the pulse (I_0) reflected and (I_T) -transmitted by the laser A_f and A_g represents respectively the attenuation of the laser beam due to the windows of the cell and the gas inside the cell (that is the CAs). In order to evaluate the gas attenuation, it is need evaluate before the absorption due to at layout adopted as attenuation of the bean splitter and wavelength dependences or conversion coefficients of energy monitor.

The dependency of the values β and A_f and this can be achieved studying the response of an empty cell (CV) and calculating for this particulate case the ratio I_T/I_1. The solution at this problem in the follow equation in given.

At the first the transmitted intensity of at empty cell is measured:

$$I_T^{CV} = I_0 A_f = (1 - \beta) \cdot I \cdot A_f. \tag{2.6}$$

So, the ratio measured with the empty cell will be (2.7):

$$\left(\frac{I_T}{I_1}\right)_{CV} = \frac{(1-\beta)\cdot I\cdot A_f}{\beta\cdot I} = \frac{A_f}{\beta}. \tag{2.7}$$

Then the value is computed for the CAs inside the cell (2.8):

$$\left(\frac{I_T}{I_1}\right)_{CP} = \frac{(1-\beta)\cdot I\cdot A_f\cdot A_g}{\beta\cdot I} = \frac{A_f}{\beta}\cdot A_g. \tag{2.8}$$

So, it is possible evaluate the attenuation A_g (2.9):

$$\frac{\left(\frac{I_T}{I_1}\right)_{CP}}{\left(\frac{I_T}{I_1}\right)_{CV}} = A_g. \tag{2.9}$$

The absorption value, $\alpha(i)$, is related to the attenuation value by eq. (2.10):

$$A_g\,(i) = \exp\left(-\alpha(i)\cdot p\cdot l\right). \tag{2.10}$$

Where p is the partial pressure of the gas, in [atm], and l is the length path of the laser beam into the cell, in [cm]. So, it is possible to obtain the absorption value, $\alpha(i)$ (2.11):

$$\alpha\,(i) = \frac{1}{p\cdot l}\ln\frac{1}{A_g} \tag{2.11}$$

and the relative error (2.12):

$$\frac{\Delta\alpha(v)}{\alpha v} = \frac{\Delta P}{P} + \frac{\Delta l}{l} + \frac{I_1}{I_T} * \frac{1}{\ln\left(\frac{I_T}{I_1}\right)} * \Delta\left(\frac{I_T}{I_1}\right). \tag{2.12}$$

2.2.1 Experimental results

The absorption laboratory layout based on the same CO_2 laser source that will be used in TELEMACO DIAL systems is used to get the absorption spectra (see figure 6, 7 and 8) that are principal characteristic of each CA.

The following figures 6, 7, 8 are three examples of the absorption spectra for toluene, trimethylbenzene and n-heptane taken placing few ppm of substance in the cell in two different conditions:

- Pure substances: condition obtained adding the substance in a cell after that a high vacuum has been reached (in the order of 0,1 mbar)

- Substance in the air: air is added in the cell starting from the above-mentioned set-up till the pressure of 1 bar is reached inside the cell.

These examples show how clear are the absorption spectra for each substance both in “pure condition” and in “real scenario conditions”. The differences between the absorption value of pure gas and an experimental condition closer to real case (air and substances) can be explained with the increase of internal pressure in this second condition,

The small discrepancy between the absorption coefficients measured in two different conditions justifies the use of CA and air to determinate the absorption value in order to realise a database of

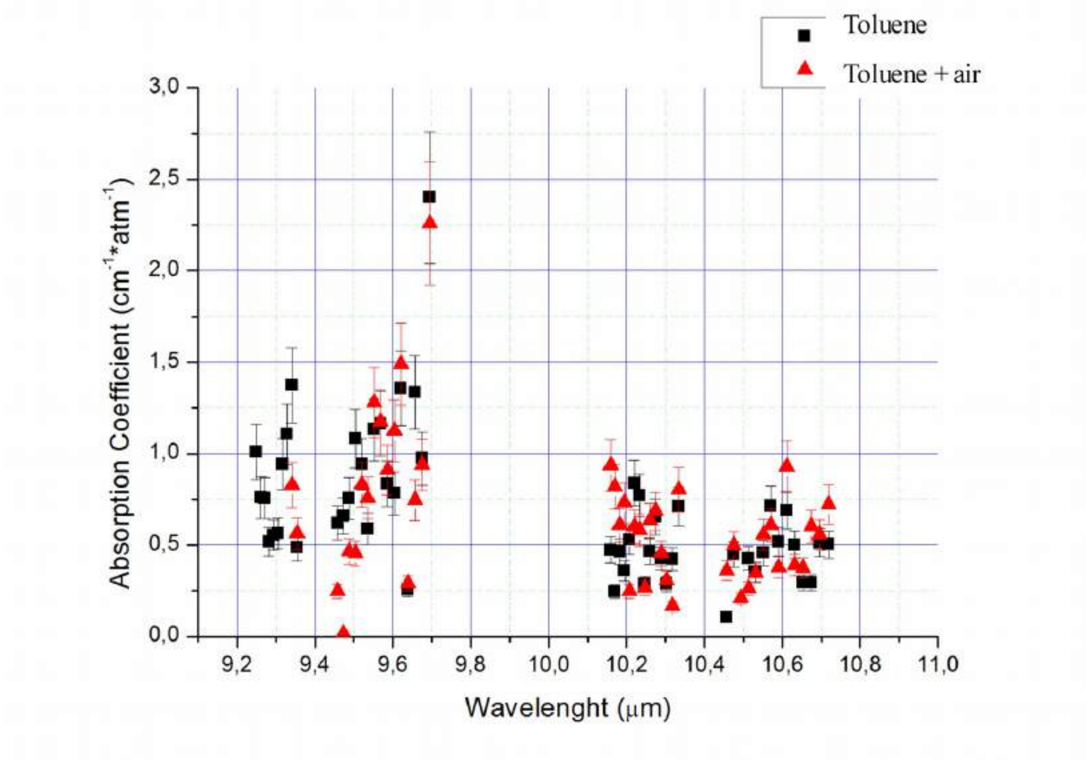

Figure 6. Absorption coefficients of toluene.

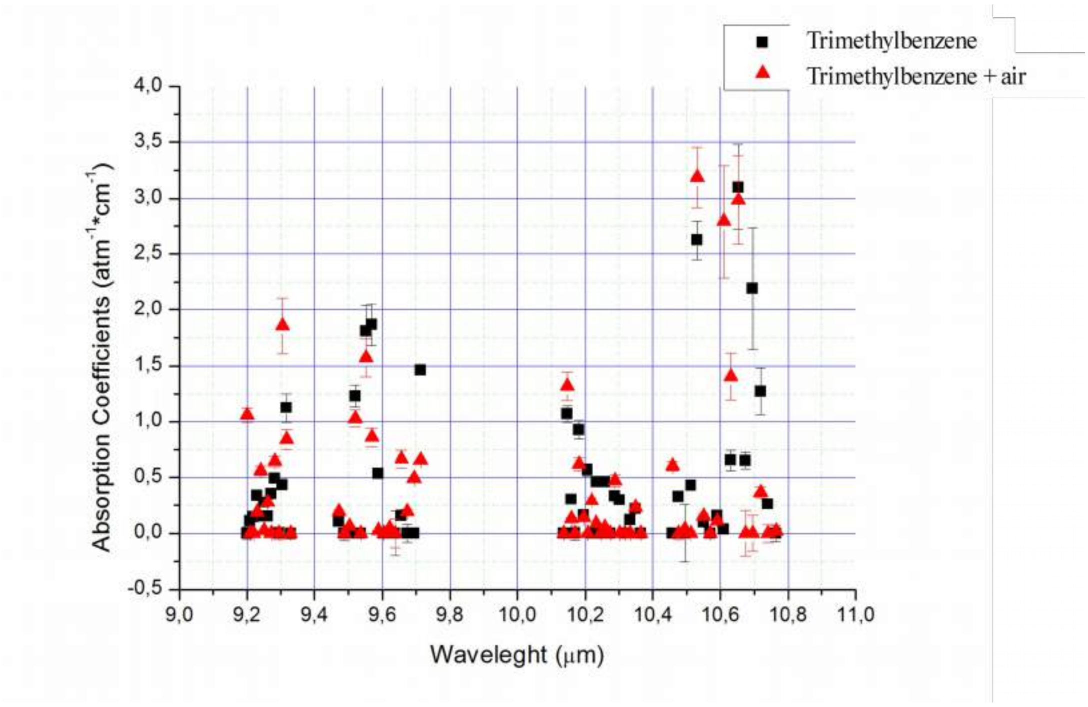

Figure 7. Absorption coefficients of trimethylbenzene.

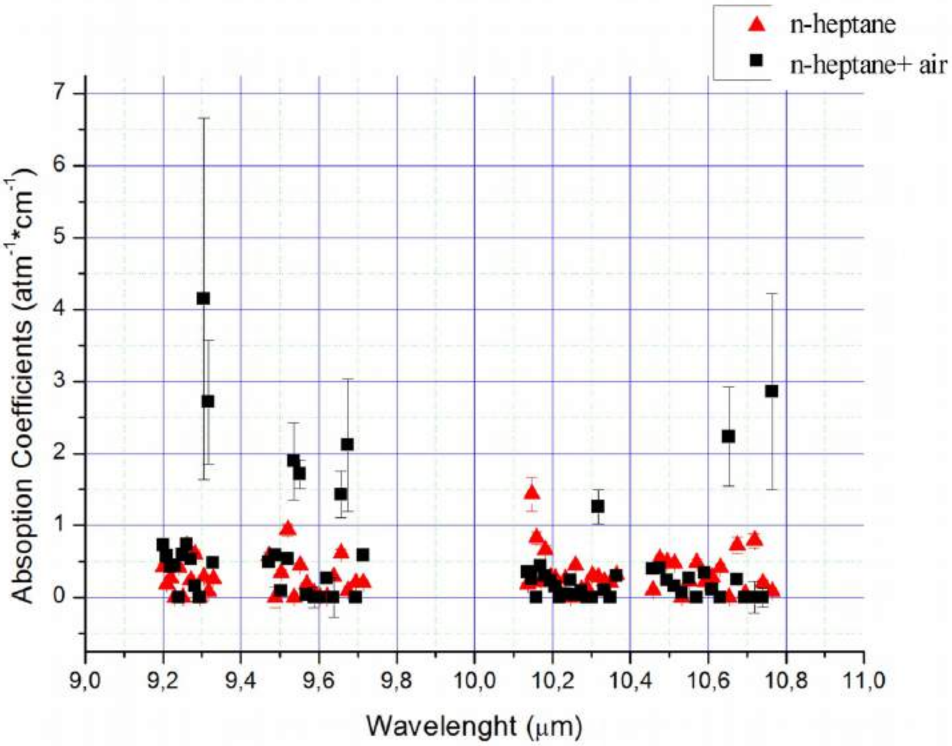

Figure 8. Absorption coefficients of n-heptane.

fingerprints. It is the starting point to get a fully database of absorptions spectra of the chemical aggressive agent's indispensable for applied the dial techniques using a multi-wavelengths approach in order to identify chemical gas in atmosphere.

The future developments of this work will be mainly two: a comparison with absorption spectra obtained with a FT-IR or similar device for the sake of the comparison and improve of the software to analyse data and discrimination.

The absorption spectra in the figures 6, 7, 8 shown that the absorption coefficients of pure substances are almost always higher than the one of substances with air.

Probably the discrepancy could be explaining by mean of line broadening effect due to a mutual interaction between the pure substances and air at atmospheric pressure. No saturation effect due to real substances are visible. This is probably due to a very small substances concentration of the order of microliter used in the absorption cell during the measurements.

Considering the aim of these measurements and the use of the database is better to acquire data using the pure substances and then create in cell a condition nearest to reality (air + substance). It is possible state that the CO_2 laser source is able to produce the absorption spectra that are clearly different and constitute the finger-prints of the TIM/TIC used for the real atmospheric experiments.

3 Conclusions

During the last fifteen years, the authors have demonstrated that laser-based optical techniques can enable a continuous, and quasi real-time, monitoring of particulate and of the CAs, in air for medium-long distances. In particular, the capability of LIDAR systems to detect CAs for the early warning phase and that of the dial systems could be used to identify at short-medium range some CAs, so the usefulness of those systems to support (once that the test in field will be done) decision making. The risks of chemical contaminations can be relevant also in healthcare settings and in a number of industrial plants; therefore, it is necessary to guarantee, in all these environments, a continuum monitoring to reduce the probabilities and the magnitude of harmful events. The authors have demonstrated that the use of optical techniques could be a viable solution. The challenges for the future are: to optimize the systems reducing the dimensions and the costs, while improving at same time the performances in terms of reduction of false alarms, to increase the robustness, the acquisition speed and the reliability during the acquisition and elaboration data phases.

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