Design and development of a compact Lidar/Dial system for aerial surveillance of urban areas

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ABSTRACT

Recently surveying large areas in an automatic way, for early detection of harmful chemical agents, has become a strategic objective of defence and public health organisations. The Lidar-Dial techniques are widely recognized as a cost-effective alternative to monitor large portions of the atmosphere but, up to now, they have been mainly deployed as ground based stations. The design reported in this paper concerns the development of a Lidar-Dial system compact enough to be carried by a small airplane and capable of detecting sudden releases in air of harmful and/or polluting substances. The proposed approach consists of continuous monitoring of the area under surveillance with a Lidar type measurement. Once a significant increase in the density of backscattering substances is revealed, it is intended to switch to the Dial technique to identify the released chemicals and to determine its concentration. In this paper, the design of the proposed system is described and the simulations carried out to determine its performances are reported. For the Lidar measurements, commercially available Nd-YAG laser sources have already been tested and their performances, in combination with avalanche photodiodes, have been experimentally verified to meet the required specifications. With regard to the DIAL measurements, new compact CO_2 laser sources are being investigated. The most promising candidate presents an energy per pulse of about 50 mJ typical, sufficient for a range of at least 500m. The laser also provides the so called "agile tuning" option that allows to quickly tune the wavelength. To guarantee continuous, automatic surveying of large areas, innovative solutions are required for the data acquisition, self monitoring of the system and data analysis. The results of the design, the simulations and some preliminary tests illustrate the potential of the chosen, integrated approach.

Keywords: Lidar, Dial, pollutants, monitoring system, UMEL, aerial surveillance.

1 Surveying urban areas with instruments based on the Lidar/Dial techniques

Since the advent of agriculture cities have kept increasing practically all over the world. In the year 2006 the humans living in urban areas have reached 50% of the entire world population and it is estimated that by 2050 more than 75% of humanity will be living in cities [1]. These areas of high density of people are unfortunately vulnerable to increasing pollution and to terrorist attacks. Therefore surveying relative large areas in an automatic way, for early detection of harmful chemical agents, has become a strategic objective of both defence and public health organisations.

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Most atmospheric pollutants are in a gaseous state in concentrations that vary between 0.01 and 10 ppm for molecules and between 0.01 and 10 ppb for metal vapors. These substances can be detected by point monitoring stations but this type of technology presents several limitations when vast, urban areas have to be surveyed. The Lidar-Dial techniques are widely recognized as a cost-effective alternative to monitor large portions of the atmosphere. Several applications have used, successfully, these techniques to measure stratospheric parameters in order to obtain experimental data to benchmark atmospheric models. Other authors are using the Lidar technique in the field of environmental monitoring but most of the solutions reported in the literature work in the UV or visible region [2, 3, 4, 5]. On the other hand, it is worth trying to extend the range of operation to the infrared spectral region where there are many molecular absorption bands. Indeed, the vast majority of the substances to be detected (SOx, ammonia, ozone etc) emit and absorb in the spectral range between 9 and 11 μm. Furthermore a wide atmospheric spectral window is located between the wavelength of 8 and 12 μm, mainly in the low troposphere where more strict should be the control of the pollution levels. This characteristic of the atmosphere allows working without significant attenuation by the main components of the atmosphere (CO_2 , H_2O) [6, 7].

The Lidar-Dial techniques are widely recognized as a cost-effective approach to detect pollutants in the atmosphere but, up to now, they have been deployed almost exclusively as ground based stations. The design reported in this paper concerns the development of a Lidar-Dial system compact enough to be carried by a small airplane and capable of detecting sudden releases in air of harmful and/or polluting substances. The proposed approach consists of continuous monitoring of the area under surveillance with Lidar type measurements. Once a significant increase in the density of backscattering substances is revealed, it is intended to switch to the Dial technique to identify the released chemicals and to determine its concentration. In this paper, the design of the proposed system is described and the simulations carried out to determine its expected performances are reported. In particular, the next section provides an overview of the entire system. In section 3, the details of the design, from the laser sources to the optics and the detectors, are described. The following section 4 describes the innovative solutions required for the data acquisition and data analysis to guarantee both the proper operation of the system and the required automatic level of interpretation of the measurements. Summary and the lines of the future implementation are the subjects of the last section of the paper.

2 Overview of a compact system for aerial detection of pollutants

The application of the system to aerial surveillance of urban areas poses some quite stringent specifications. First of all the system must be compact and its weight should not exceed 15 Kg. Robustness, ruggedness and proper operation in all atmospheric conditions must also be guaranteed. At the same time, the power of the sources and the sensitivity of the detectors must provide an operational range in excess of 1 Km. Practical aspects, from the simplicity of the alignment to the stability of the system, must be given proper attention.

As mentioned, to meet the aforementioned requirements, the proposed approach, consisting of continuous monitoring the area to be surveyed with the Nd:YAG laser [8] and, after detection of variations in the aerosols, the accurate concentration measurements with the CO_2 laser [9], is therefore to be considered a viable solution. Various simulations, reported in [10], indicate that both lasers can provide measurements with a more than acceptable SNR over the whole distance range required by the specifications. The sensitivity of the measurements seems also to be adequate to the application of pollutant detection. The block diagram of the system is reported in Figure 1, reporting a block diagram of the entire station. The lasers and the acquisition systems, including detectors and digitizers, are to be supervised by a Monitoring and Management system. The main goal of this unit consists of automatically activating the concentration measurements with the CO_2 laser once something anomalous is revealed by the Nd:YAG laser system. Both the logbook of the system functionalities and the data stored are meant to be made available to a human operator in remote control unit of the department responsible for the operation of the monitoring station. On the other hand, an Artificial Intelligent (AI) system is meant to be run continuously for a direct communication of alarms to the “Control Room” (CR) of the institution with the responsibility to react in the case the limits in the concentrations of the pollutants are exceeded.

The main challenges of an automatic, aerial system are due to the requirements of compactness and reliable operation. They have been addressed by careful design of the hardware (section 3) and by the adoption of innovative solutions for the system control and data analysis (sections 4).

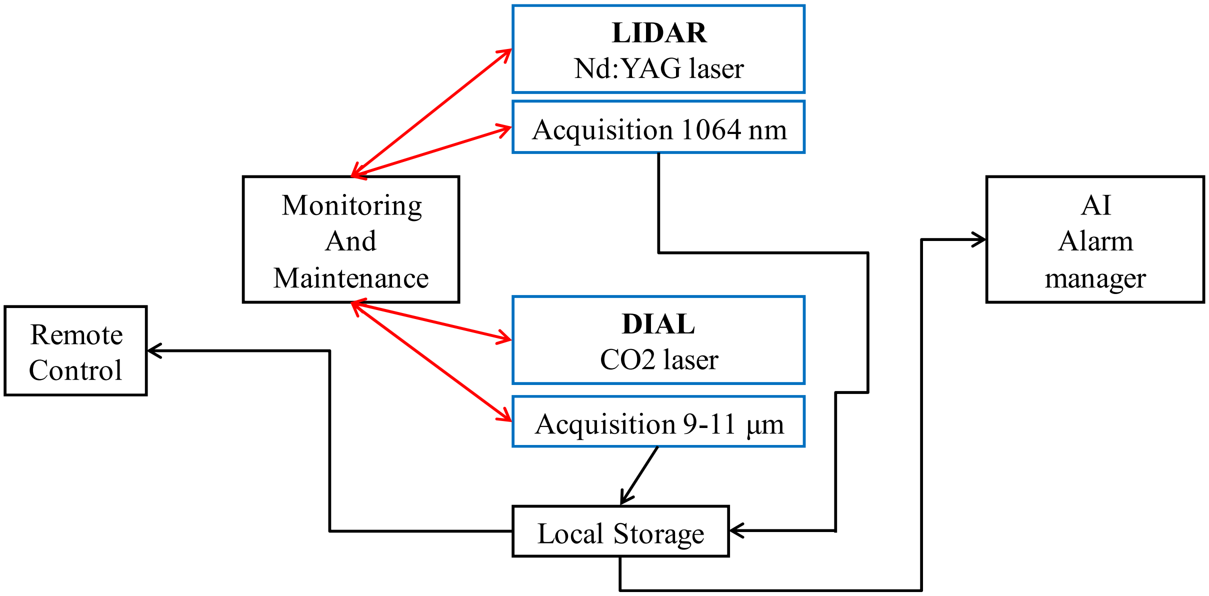


Fig.1: Block diagram describing the main elements of the aerial system.

3 Details of the design

3.1 Laser sources

For the Lidar measurements, commercially available Nd:YAG laser sources have already been tested and their performances, in combination with avalanche photodiodes, have been experimentally verified to meet the required specifications [10]. The choice of these components is mainly dictated by the need of developing a compact system, robust enough to guarantee continuous (24/7) operation in hostile environments. These technologies have also become relatively standard and therefore they can be procured at reasonable costs [11, 12]. The compactness of this laser can be appreciated from Figure 2.

Concerning the DIAL measurements, the system is based on a new compact CO_2 laser source operating at the wavelengths ranging from 9 to 11 µm. This laser covers with about sixty laser lines a spectral region where there is good absorption for several atmospheric and organic molecules and it is also eye safe. The energy per pulse of about 50 mJ typical, is sufficient for a range of at least 500m. The source is pulsed with pulse duration equal to 50ns. The divergence of the output beam is equal to 1 mrad and the diameter of 6 mm. The maximum frequency of repetition (PRF) is 100Hz. The main characteristics of the selected CO_2 laser source are reported in Table I. The laser also provides the so called "agile tuning" option that allows to quickly tune the wavelength.

Fig.2: CFR Laser Head.

Transmitter	
Active medium	CO_2
Emission Type	Pulsed
Spectral Range	9.2 – 10.8 μm
Maximun Pulse Repetition Rate	100Hz
Beam divergence	1mtad
Beam waist diameter	6mm
Pulse duration	100ns
Pulse Energy	100mJ
Power supply	240, 10A, 50/60Hz

Table I. Parameters of CO_2 laser source.

3.2 Optical system

The optical design has been carried out with the help of the software package ZEMAX. The best solution identified consists of a Newtonian telescope, which unlike other configurations, presents a higher brightness at the expense of a lower image quality (more aberrations), and whose basic components are optical reflective, commercially available in order to reduce cost. Given the requirements of robustness and reliability of the foreseen applications, it has been decided to adopt focus industrial electronic components that can be mounted on a rugged system and that, in addition to being stable, allow data acquisition in real time and fast data storage. An overview of the optical layout is presented in Figure 3. The most critical component is a Germanium beam splitter, which allows separating the two backscattering wavelengths (Nd:YAG and CO_2) and sending them separately to the respective detectors. The typical transmission curve of this optical material is reported in Figure 4.

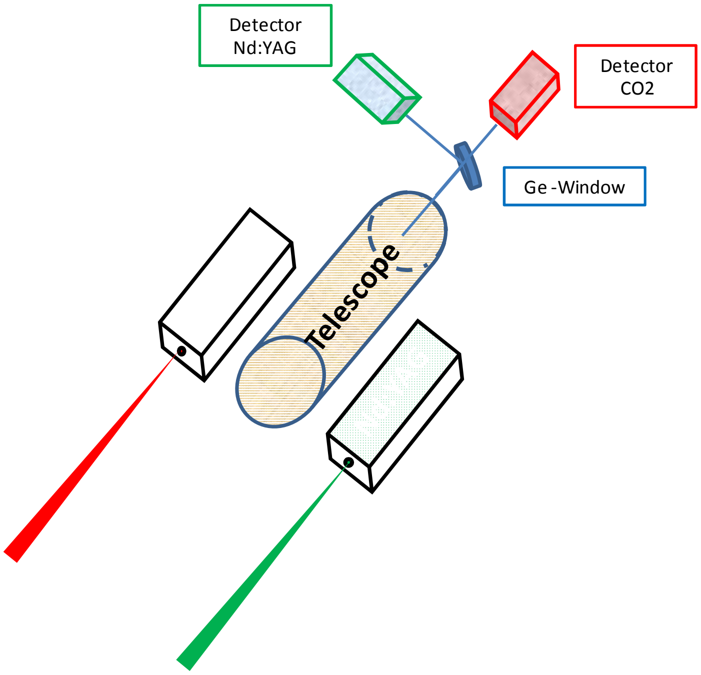


Figure 3: Layout of the optical part of the system**.**

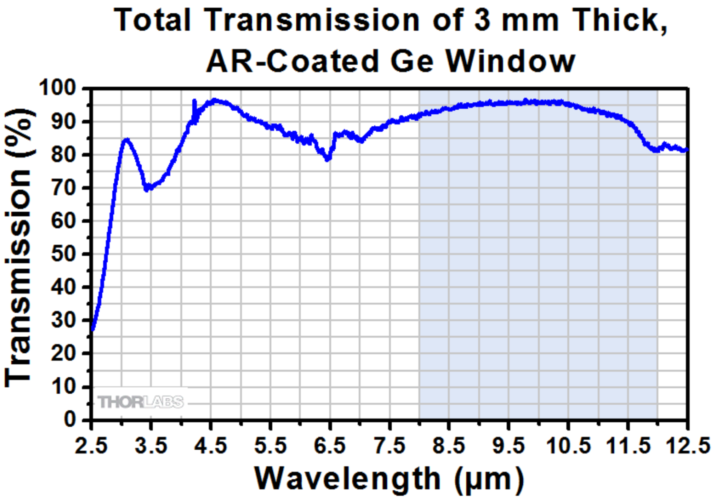
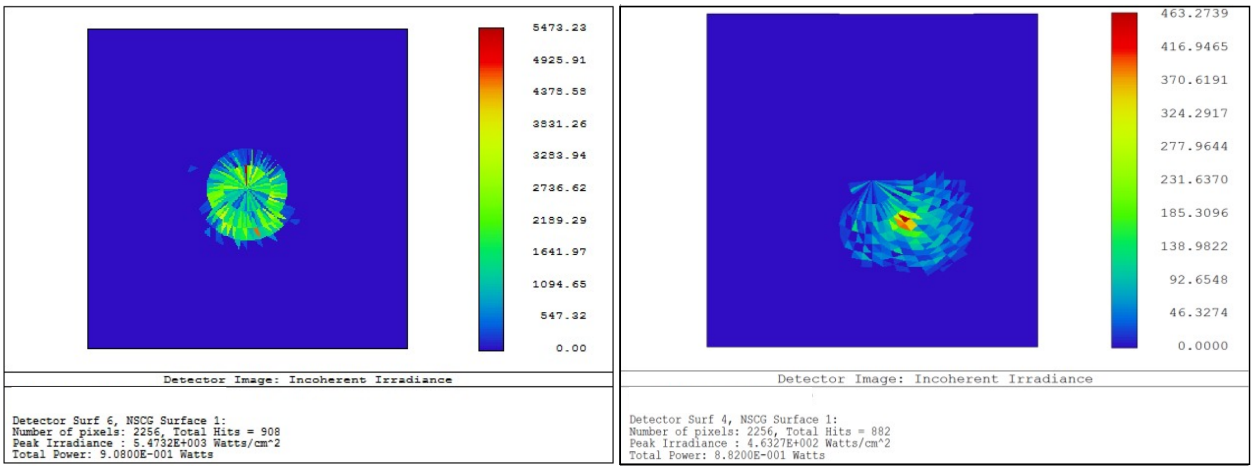


Figure 4: Optical transmission of the Germanium window [13].

The envisaged application of the system, aerial surveillance, requires paying particular attention to the resilience of the optics to misalignments. This issue has been investigated in detail. ZEEMAX simulations have been carried out to determine the maximum level of misalignment of the optical components that does not jeopardize the measurements. The following figure 5 provides a graphical representation of the results. In detail, figure 5a shows the detected spot in the case of perfect location of the optical component (correct alignment of the optics). In this ideal case, 90% of the backscattered radiation reaches the detector. On the other hand, figure 5b illustrates the case of detection when the tolerances in the mechanical assembly are taken into account (1 mm accuracy in the distance between the mirrors, 0.1 mm accuracy in the location of the CO_2 detector, 0.05^0

maximum angular misalignments with respect to the axis of the telescope). The results are very encouraging since even assuming the worst case scenario, 85% of the backscattered radiation still reaches the detector.



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Detector Surf 6, NSCG Surface 1:
Number of pixels: 2256, Total Hits = 908
Peak Irradiance : 5.4732E+003 Watts/cm^2
Total Power: 9.0800E-001 Watts
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Detector Surf 4, NSCG Surface 1:
Number of pixels: 2256, Total Hits = 882
Peak Irradiance : 4.6327E+002 Watts/cm^2
Total Power: 8.8200E-001 Watts
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Figure 5: Left) detected spot in the case of perfect alignment of the optics; Right) detected spot in the case the tolerances in the mechanical assembly are taken into account.

3.3 Detectors

The detector chosen for the Nd:YAG laser is an Avalanche PhotoDiode (APD), whose characteristics are summarized in Table II. The main thing to verify is that the proposed combination of laser source-detector can provide the require SNR over the specified range.

APD **EG&G C30954/5E**	
Spectral response	400 nm ÷ 1100 nm
Bandwidth	DC-200 MHz
Responsivity @ 1060 nm	0.5 (normalized)
NEP	0.3 pA/√Hz
Output impedance	50 Ω
Detector size	1.5 mm (dia)
Power supply	+/- 15 V

Table II. Parameters of Nd:YAG Lidar system.

The SNR is mostly determined by the optical detector and the signal power incident on the detector element. In our application and given the characteristics of commercial pulsed laser systems, the received power levels can be regarded as high enough to be well above the background. In this approximation, the dark current I_D and the thermal noise term, which is reduced by the high avalanche gain *M*, can be neglected so that the SNR for an avalanche photodiode can be calculated from the simplified relation [4]:

$$SNR = \frac{1/2 \cdot R \cdot m^2 \cdot P_r}{2 \cdot q \cdot F(M) \cdot B} \quad (1)$$

Where:
P_r is the received optical power
m is the modulation index
M is the avalanche gain
$F(M)$ is the excess photodiode noise factor $=M^x$ with $0 < x \leq 1$
B is the effective noise bandwidth
R_{eq} is the equivalent resistance of photodetector and amplifier load

and R is the responsivity calculated as:

$$R=M^*(\eta^* q)/(h^* \nu) \quad (2)$$

with η the quantum efficiency, q the electron charge, h the Planck's constant and ν the frequency of a photon. Furthermore, $m = 1$ for pulsed signals, because the laser is switched on and off. This means that the SNR is directly proportional to the received optical power P_r and the responsivity R and inversely proportional to the bandwidth B. In its turn, the bandwidth B is a function of the sample rate and pulse duration, respectively; the shorter the pulse the higher is the required bandwidth. However, a larger bandwidth means lower SNR if P_r is kept constant. The expected SNR for the proposed system, as calculated on the basis of equation (1), has been simulated for a range of gain M between 2 and 10, as reported in [10]. The SNR remains well above 100 up to more than 2.5 km and can therefore be considered more than satisfactory for our application.

For the detection of the backscattered CO2 signal, the chosen detector is a HgCdTe photodiode, cooled at the temperature of 77 K and manufactured by the Kolmar Technologies. The model KV104 presents a detectivity $D^*=3\times10^{10}$ Jones and a responsivity of 4 Amp/Watt. Since the bandwidth is of 100 MHz, the defector is suitable for the detection of short pulses of the order of 10 ns.

4 Data acquisition, control system and software development

Since the detection of dangerous substances must be performed in an automatic way, the aerial system will be equipped with an adequate set of control and communication devices for independent autonomous operation and for communication with ground base stations. With regard to the data acquisition, the standard PXI (PCI eXtensions for Instrumentation) is considered the most suited to provide the required performance in terms of robustness, reliability and real time performance. The present design therefore comprises a PXI controller, located in a PXI chassis together with an Oscilloscope/Digitiser and an I/O card. The PXI system also includes a 2 axis stepper motor, with relative encoders, for the control of the optics. These are all commercial components already tested and proved adequate for the application. The required control software will be implemented using Labview Real Time, in order to maximize the efficiency and speed. In this way we expect that the computational time will not be a critical element in determining the minimal interval between subsequence measurements.

Particularly delicate, from the point of view of the reliability of the measurements over long periods of time, is the stability of the CO_2 laser sources, which has shown in the past a tendency to drift relatively to each other. Of course, if the times of the laser pulses are not exactly synchronized, the Dial measurements can be completely compromised and therefore the estimation of the pollutant concentration incorrect. This issue can be solved by a time realignment of the pulses provided a reliable automatic technique for the determination of the time instants of the laser pulses is available. Typically the identification and time location of these events is achieved by means of visual analysis of the detected signals (normally waveforms of amplitude versus time). Of course this is not possible in the case of automatic surveying systems, which cannot be manned all the time, even assuming that operators could guarantee the required level of reliability. Therefore a new technique, called the Universal Multi Event Locator (UMEL), has been applied to this problem. UMEL is a universal technique because it is independent of the type of the pattern sought (peaks, drops or slope changes) and the type of waveforms analysed (time domain or frequency domain). UMEL is based on Support Vector Regression (SVR)

[14], a version of SVM [15] for function estimation. SVR fits the training data without depending on factors such as sampling rate or noise distribution. This technique computes a fitting function and, in addition, it retrieves a list of the points from the training set that become Support Vectors (SVs). These specific points are original samples of the signals, another advantage of the method, which gives outputs not based on any manipulations of the original measurements.

SVR uses the e-insensitive loss function, also called e-tube:

$$|\xi|_e = \begin{cases} 0 & \text{if } |\xi| \le e \\ |\xi| - e & \text{otherwise} \end{cases} \qquad (3)$$

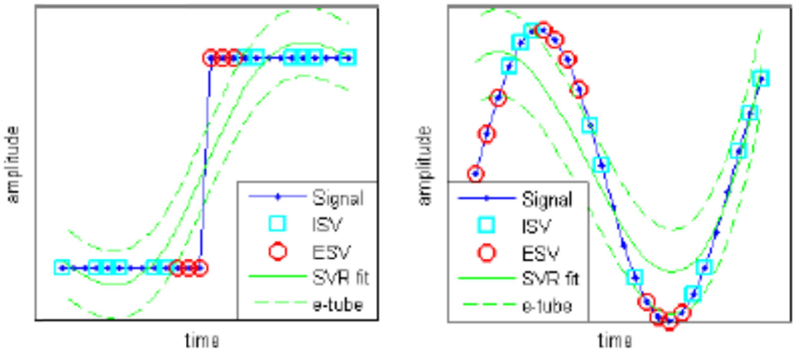
The goal of SVR is to find the flattest function that fits the training data within the e-tube. The errors lower than e are not taken into consideration (the value of the e-insensitive loss function is 0 in the region [ξ [-e;+e]) but the errors higher than e are minimised. It is therefore possible to define the e-tube in such a way that the normal variations in the signals, including noise, remain within it and the specific events to be detected fall outside this interval.

UMEL can be used as an exact locator of singular points within signals. To achieve this, UMEL gives a novel interpretation of the SVs. In SVM and SVR, the complexity of the model determines the number of SVs (the higher the complexity, the larger the number of SVs). The regression of complex data sets requires large numbers of SVs. In contrast, simple data sets require smaller numbers of SVs. But the number of SVs does not depend only on the complexity of the data set to regress. It also depends on the smoothness of the regression function. Smoother functions require fewer SVs than crispy functions. Using UMEL, not all the SVs have the same degree of relevance. The SVs that lie on or outside the e-tube are called External Support Vectors (ESVs). In contrast, the SVs within the e-tube are called Internal Support. They are defined by the relations:

$$\begin{aligned} &ESV \subseteq SV \quad \forall i \in ESV, \quad |y_i - f(x_i)| \ge e \\ &ISV \subseteq SV \quad \forall i \in ISV, \quad |y_i - f(x_i)| < e \end{aligned} \qquad (4)$$

ISVs are necessary samples for the regression estimation, but they do not provide the same degree of relevance that can be assigned to ESVs. UMEL is based a novel interpretation of ESVs: the SVs that become ESVs are the most difficult samples to regress (they cannot be fitted inside the e-tube) and these SVs provide essential information in the regression process. ESVs reveal the occurrence of special patterns inside a signal: peaks, high gradients or segments with different morphological structure in relation to the bulk of the signal.

Figure 6 shows two examples of UMEL using a step function and a sinusoidal function. The green dashed lines delimit the e-tube. Then, the SVs within these lines are ISVs (cyan squares) and the SVs outside the e-tube are ESVs (red circles). The ESVs are clearly the most difficult samples to regress. In the case of the step function (Figure 6a), the samples around the step become ESVs. The ISVs are found inside the e-tube. In the case of the sinusoidal function (Figure 6b), the ESVs appear at the beginning of the function and at the external points corresponding to the maximum and the minimum of the function.



(a) Step function (b) Sinusoidal function

Figure 6: UMEL fit to a step and a sinusoidal function.

In many signals of relevance for atmospheric physics, and certainly in all those obtained with Lidar techniques, the relevant information resides in the high frequency components in the time domain (spikes, drops, rapid slope changes, etc.). Therefore, it is possible to apply UMEL to locate these events. All the mathematical details about UMEL can be found in [16].

The application of UMEL to the location in time of the laser pulses is illustrated in Figure 7. As mentioned, the basic concept of the Dial system involves the measurement of the intensity of the backscattered radiation from a laser pulse. For the simplest case, two laser frequencies (λ_{ON} and λ_{OFF}) are selected such that λ_{ON} (red curve in figure 7) and λ_{OFF} (blue curve in figure 7) are on-resonance and off-resonance, with respect to an absorption transition of the molecular species whose concentration is to be measured. The concentration of the absorbing species can be deduced from the differential absorption of the backscattered laser radiation at wavelength λ_{ON} compared to that at λ_{OFF} .

The location process begins with normalisation of the signals and then continues with the search of the peaks. More than one ESV appears on each peak. The next step therefore concentrates all the ESVs of each peak in a single one. After this task, each peak is represented by just one ESV. By properly determining the level of the e-tube, it is possible to guarantee that the noise level do not affect the location of the peaks which are therefore all to be interpreted as laser pulses.

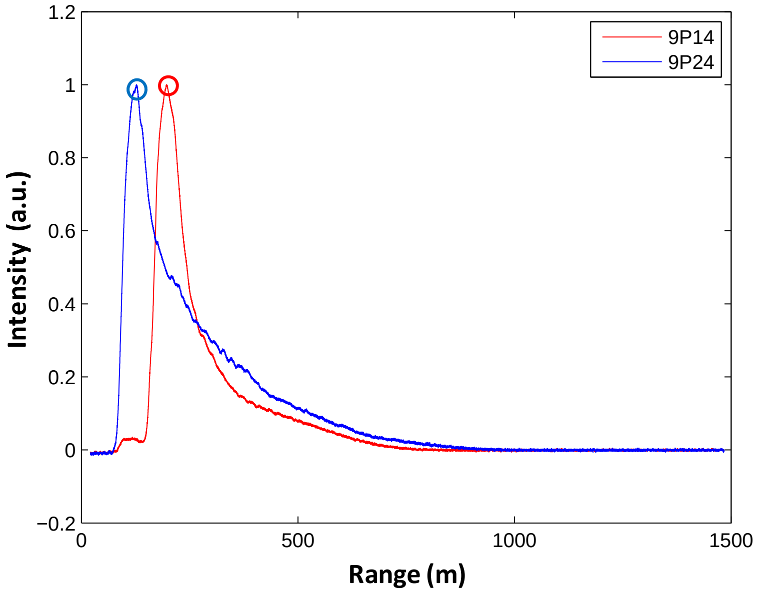


Figure 7: Location of the laser pulses with UMEL. Laser lines generally used for Ozone DIAL measurements. The circles indicate the laser peaks identified with the external support vectors by UMEL.

The advantages of UMEL, compared to hardware other software solutions, are the costs and improved time resolution. Being a method based on data analysis, no additional hardware is required. Moreover, since the method basically utilizes the samples of the acquisition system without any filtering of smoothing, the time resolution is in no way reduced. This last point also constitutes a major progress compared to other data analysis techniques, which typically require some manipulation of the signals reducing their bandwidth.

5 Summary and next steps

The design of a Lidar/Dial system for the detection of pollutants in urban areas has been completed. The envisaged application is aerial surveillance, which imposes quite stringent requirements in terms of compactness, robustness and reliability. The various parts of the system have been tested separately and found more than adequate to meet the specifications. The next steps will therefore consist of the integration of the system, followed by an extensive set of measurements campaigns for the qualification of the final performances. Particular attention will have to be devoted to the developments of suitable data analysis techniques, to provide the required information in an automatic way, with minimum human intervention. The application of the innovative technique called UMEL seems particularly promising for both the stabilization of the system and the interpretation of the measurements.

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