Automatic localization of backscattering events due to particulate in urban areas

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ABSTRACT

Particulate matter (PM), emitted by vehicles in urban traffic, can greatly affect environment air quality and have direct implications on both human health and infrastructure integrity. The consequences for society are relevant and can impact also on national health. Limits and thresholds of pollutants emitted by vehicles are typically regulated by government agencies. In the last few years, the interest in PM emissions has grown substantially due to both air quality issues and global warming. Lidar-Dial techniques are widely recognized as a cost-effective alternative to monitor large regions of the atmosphere. To maximize the effectiveness of the measurements and to guarantee reliable, automatic monitoring of large areas, new data analysis techniques are required. In this paper, an original tool, the Universal Multi-Event Locator (UMEL), is applied to the problem of automatically indentifying the time location of peaks in Lidar measurements for the detection of particulate matter emitted by anthropogenic sources like vehicles. The method developed is based on Support Vector Regression and presents various advantages with respect to more traditional techniques. In particular, UMEL is based on the morphological properties of the signals and therefore the method is insensitive to the details of the noise present in the detection system. The approach is also fully general, purely software and can therefore be applied to a large variety of problems without any additional cost. The potential of the proposed technique is exemplified with the help of data acquired during an experimental campaign in the field in Rome.

Keywords: Lidar, Particulate, Support Vector Regression, UMEL.

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1 The measurement of particulate with LIDAR techniques in urban areas

In the last decades, Lidar and dial techniques have become well established laser based methods for the remote sensing of the atmosphere [1]. They are often used to probe almost any level of the atmosphere and to acquire information to validate theoretical models about different topics of atmospheric physics. They can also be deployed for environment surveying of particulate and molecule concentrations [2-10].Most pollutants are present in the atmosphere in a gaseous state in concentrations between 0.01 and 10 ppm for molecules and between 0.01 and 10 ppb for metal vapours. Generally, in order to detect such substances and determine quantitatively their concentration, point monitoring stations are employed. These fixed monitoring stations implement different measurement techniques with integration times varying from one minute to a few hours. Unfortunately they can typically evaluate the concentration of the substance, for which the system has been calibrated, only in a limited area close to the detector. So, to cover large areas, these fixed monitoring stations have to be deployed in large numbers. They have also to be connected in suitable networks. In addition to the practical difficulties and the economic implications, it is to be emphasized that no sound methodology exists to determine the optimal number of measurement points and their localization. Therefore, all these reasons motivate the development of a sensitive, flexible and fast method with the capability of measuring concentrations of atmospheric gaseous pollutants over a wide range. With the development of reliable lasers, emitting in the appropriate range of wavelengths, Lidar and Dial systems have become suitable and competitive techniques [11, 12, 13].

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In this paper, Lidar measurements are performed to show the potential of the technique to monitor particulate matter in urban areas. The capability of the proposed technique is exemplified with the help of data acquired during an experimental campaign in the field. As in practically all the applications of Lidar/Dial systems to atmospheric physics, also the present study relies on the capability of properly detecting the backscattered peaks of radiation.

A typical example of the use of Lidar in the detection of backscattered peaks is the detection of forest fires [3, 4, 6, 11]. In this paper we present another application, the study of particulate emission by urban traffic. A continuous monitoring of particulate over a small ring road has permitted to study the traffic flow during diurnal and evening periods.

In pioneering tests, this can be done manually but such a solution is no viable for systematic applications. In this respect, automatic analysis techniques can help substantially when results of very large surveys have to be analyzed or when real time alarms have to be reliably guaranteed. The measurements have therefore been analysed with an original tool, the Universal Multi-Event Locator (UMEL) [14, 15], applied to the problem of automatically indentifying the time location of peaks in the received signal. The method developed is based on Support Vector Regression and presents various advantages with respect to more traditional techniques. In particular, UMEL is based on the morphological properties of the signals and therefore the method is insensitive to the details of the noise present in the detection system.

With regard to the structure of the paper, an overview of the Lidar system used to perform the measurements is reported in the next Section. Section 3 provides the details of the experimental campaign performed, whose results are reported in Section 4. The new automatic data analysis methods are described in Section 5 and their application to the specific measurements of the described campaign are the subject of Section 6. In Section 7 some lines of future investigation are provided.

2 The system

The measurements described in the paper have been performed with the mobile Lidar unit of Industrial Engineering Department, University of Rome "Tor Vergata". The system consists of an assembling an easily transportable compact lidar system. The transmitter is constituted by a Nd:YAG laser and the receiver system is based on a Newtonian telescope and a photomultiplier tube. The whole system is mounted on altazimuthal system [16, 17].

2.1 Overview of the system

The lidar system develop by the Quantum Electronic and Plasma Physics group at the University of Rome Tor Vergata consists of a mobile system based on Nd:YAG laser as transmitter that can operate at three wavelengths: 1064, 532 and 355nm. The laser is anchored at the receiver system, a Newtonian telescope, and both can move to direct the beam and receive the backscattered radiation over a whole hemisphere. The system is completely auto-powered and the structure is designed to be transportable and steerable. It is easily hooked to azimuth mount for supporting and rotating about two mutually perpendicular axes; one vertical, from -10° to 90°, and one horizontal, from 0° to 220°. By means of two step-motors, it has a global angular resolution of 1.8°. These technologies have become relatively standard and therefore they can be procured at reasonable costs [18].

2.2 Transmitter system: laser source

A solid-state compact Nd:YAG Laser has been already used for the Lidar measurements. Pulsed Nd:YAG lasers are typically operated in so-called Q-Switching mode. The model mounted on our mobile system is a Brilliant, produced by Quantel. It is optically pumped and can generate laser light at the fundamental harmonich 1064nm and two 532 and third harmonic 355 nm. To obtain the measurements presented in this paper, the third harmonic has been used. The laser source parameters are listed in Table I. The choice of this component is mainly dictated by the need of developing a compact system, robust enough to guarantee continuous operation. This technology has also become relatively standard and therefore it can be procured at reasonable costs [19].

Table I. Parameters of Nd:YAG laser source.

Laser Source	
Active medium	Nd:YAG
Emission type	Pulsed, Q-Switched
Output Power	1.2 W (@ 355 nm)
Pulse Repetition Frequency	10Hz
Beam divergence	0.5 mrad
Beam waist diameter	(5±0.02) mm
Pulse duration	4 ns
Pulse energy	120 mJ
Power supply	100-240 V, 10 A, 50/60 Hz

2.3 Receiver system

The optical design has been carried out with the help of the optical design software ZEMAX. The best identified solution consists of a commercial Newtonian telescope which, unlike other configurations, presents a higher brightness at the expense of a lower image quality (more aberrations), and whose basic optical components are reflective and commercially available to reduce cost. For the telescope parameters see Table II.

Table II. Parameters of telescope.

***Newtonian Telescope,* Auriga Model**	
Distance between the two mirrors (along the optical axis)	(820.00 ± 1.00) mm
Nominal focal length	1030 mm
Primary mirror diameter (parabolic)	(210.00 ± 1.00) mm
Secundary mirror diameter (plane)	(35.00 ± 0.02) mm
Internal telescope radius	(120.00 ± 0.5) mm
External dimensions	(1000 ± 1) mm × (255 ± 1) mm
Field of View	$\phi = (2.5 \times 10^{-4})° = (4.3633 \times 10^{-4}) rad$
Telescope's area	(337.00 ± 7) cm^2

2.4 Detector

Since the laser source is operating in the UV region, the detector chosen is a Hamamatsu's photomultiplier tube (PMT), R3235 model, whose characteristics are summarized in Table III.

Table III. Parameters of the detector.

***PMT,* Hammatsu R3235**	
Spectral Response	160 nm ÷ 650 nm
Dark Current	1 nA
Responsivity	57.114 mA/W @ 355 nm
Time Response	30 ns
Output impedance	50 Ω
Minimum Effective Area	10 mm (diameter)
Quantum Efficiency	20%

3 Overview of the measurement campaign

Tracking of two-dimensional spatial and temporal aerosol distributions has been performed using scanning elastic LIDAR, operating at 355 nm. Based on the data we have collected, we have investigated the flow dynamics and the aerosol concentrations within the lower troposphere and found evidence of daily aerosol cycles.

3.1 System's location

As already mentioned, the principal objective of this work is the study of particulate emitted by vehicles in strongly congested urban areas. It is possible to perform a detailed analysis of the most sensitive parameter to describe this topic, using active sensing Lidar techniques. In fact, the backscattering coefficient – $\beta(\lambda,R)$ $[m^{-1}sr^{-1}]$ indicates the portion of the radiation scattered by several atmospheric constituents and largely due to particulate (at angles from 90° to 180°), and it is called the backscatter cross-section for unity surface area [2].
From the literature [20, 21, 22], it is known that variations of β, as a function of distance or time, indicate the increase of the presence of PM [11] or in specified case of and water vapour [12, 13] in excess in the atmosphere and identify the variations of the concentration along the laser line of sight.
This study reports the results of an experimental campaign performed in Rome on the 16th to the 18th of December 2013. The analyzed area is the roundabout near the General Hospital of Tor Vergata. In Figure 1, a satellite image of the area is shown, obtained with *Google Earth* software. The absolute geographical coordinates of the system, the Line Of Sight - LOS (tilted of ~ 50° to the Northeast) are reported and the most congested points or the possible obstacles are marked by numbers.

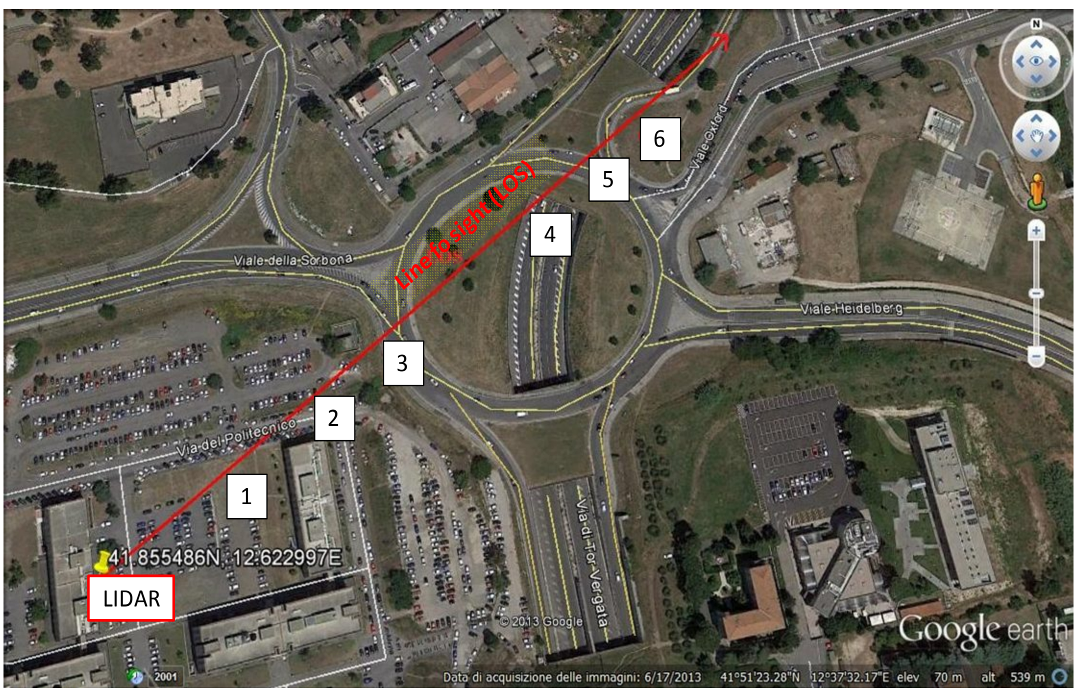

Figure 1. Position of System and Line of Sight (LOS). Legend: 1) Car-parking University (50 -60 m); 2) Via del Politecnico (95-116 m); 3) South West half of roundabout , Via della Sorbona (174-194 m); 4) Tunnel, Via di Tor Vergata(272-284 m); 5) North East of roundabout, Viale Heidelberg (300-318 m); 6) Viale Oxford

In this work we are not interested to explore a large area, but only to evaluate, in a fixed direction, the variation of particulate due to a urban traffic as a function of time (daily cycle) and distance. On the basis of these considerations, the laser-telescope system direction has been fixed. The Lidar is lifted 2.2 m above ground, it has also a pointing angle of 5° and a fixed LOS.

3.2 Traffic in the area

As mentioned in the previous sections, the main objective of the experimental campaign consists of demonstrating the capability of the system to monitor the particulate emitted by road traffic in the area. Indeed, the variability of the traffic intensity strongly influences the emission of pollutants in the atmosphere. Therefore, the experimental results, in particular, the backscattering coefficient, as a function of distance and acquisition's time, have to be correlated with the variations in the traffic of the monitored area.

To interpret the results of the experimental campaign, a study has been performed to determine the intensity of the vehicular traffic at Tor Vergata's roundabout in front of the Tor Vergata General Hospital. Figure 2 shows the traffic of the area on a typical Tuesday working day.

Thanks to the functionalities of Google Maps, it is possible to determine the annual average traffic intensity in the area and in a specific day of the week: Tuesday from 9:30 a.m. up to 06:00 p.m. The analysis has been focused on this period because this work concerns results and data acquired by the Lidar system during the experimental campaign performed on Tuesday the 17^{th} of December 2013.

Concerning the system's LOS, in this work we have concentrated on evaluating the traffic intensity in:

- two opposite points of the roundabout: in front of Tor Vergata General Hospital, or the final part of Sorbona and Heidelberg Streets, point 3 and 5 of Figure 1, respectively;
- in the central position of Figure 1, the tunnel of Tor Vergata Street, point 4;
- Oxford Street, point 6 of the Figure 1.

As you can see in Figure 2, traffic always assumes the same intensity in the two opposite points of the roundabout, with a remarkable increase around 05:30 p.m., only in the north east half (see Figure 1). Similarly, Oxford Street presents the same results (see figure 1)

Instead, traffic intensity strongly varies in the tunnel, in the middle of the roundabout (Tor Vergata Street), with an increase between 10:00 a.m., 12:00-12:30 a.m., 02:30-03:00 p.m. and after 06:00 p.m., which coincide with the rush-hours.

From a first analysis based on this data, which describes the annual average traffic in the interested area, it is possible to draw the following conclusions: traffic in the area is quite intense not only in the rush-hours but, globally, during the whole day. Particularly it results to be always quite intense during the whole day in the direction of the University and General Hospital (out of Rome city center direction). During the rush-hours (office opening and closing times) the traffic is particularly heavy in both directions, with some peaks in the first hour of the afternoon, in the subway (Tor Vergata Street) and around 05:30 p.m., between the north east half (see Figure 1) of the roundabout (Centre of Rome direction) and Oxford Street. These peaks can be justified considering closing time of the offices and the return traffic due to students and General Hospital personnel.

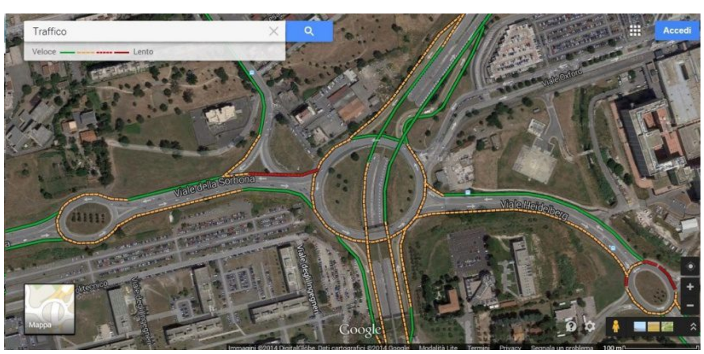

Figure 2a. Daily traffic conditions of the area at 8.30 a.m.

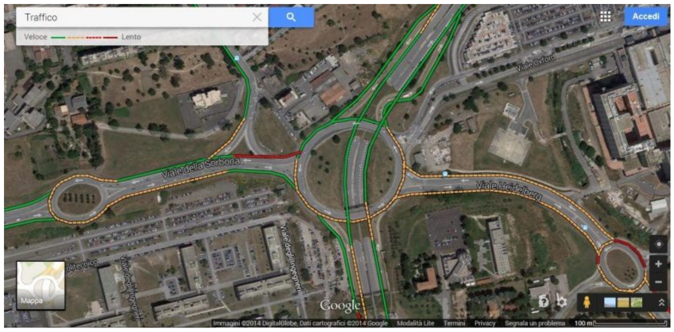

Figure 2b. Daily traffic conditions of the area at 2 p.m.

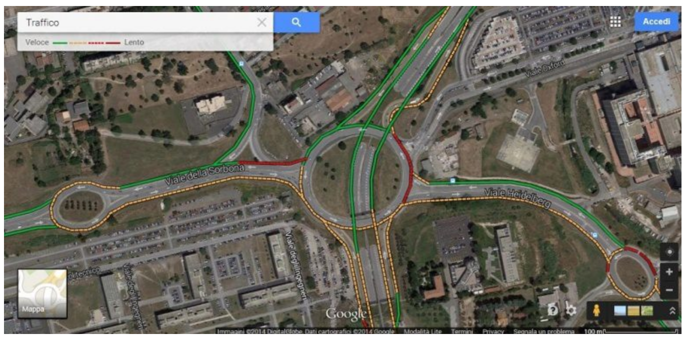

Figure 2c. Daily traffic conditions of the area at 5.30 p.m.

4 Campaign Results

The goal of this work is to find the variations of β that represent the backscattering values [m^{-1}] as a function of range and time of the acquisition. In this perspective, some specific scripts have been developed with Matlab for the processing and graphic presentation of Lidar data in the post-processing step. These scripts elaborate "raw" data acquired by the system and they implement the method of inversion known as *Slope Method* [23, 24].
For a fixed value of background intensity I_{bgnd}, the Background Power is calculated as (Rp is the detector's responsivity):

$$P_{bgnd} = \frac{I_{bgnd}}{R_p} \tag{1}$$

Finally, we obtain the *S(R) function* and the *Backscattering Coefficient* β:

$$S(R) = \ln[(P(R) - P_{bgnd}) \times R^2] \tag{2}$$

$$S(R) = \ln(\frac{\beta}{\beta_0}) - 2\alpha R \tag{3}$$

$$\beta = \beta_0 e^{[S(R)+2\alpha R]} \tag{4}$$

It is necessary to implement a further Matlab script to determine the variations of the global mean backscattering coefficient as a function of the distance and time.

The time evolution of the measured β is reported in Figure 3. It is possible to appreciate a lot of changes in colour that indicate variations of β as function of distance and time. The dark blue intervals between data sets correspond to intervals without measurements.

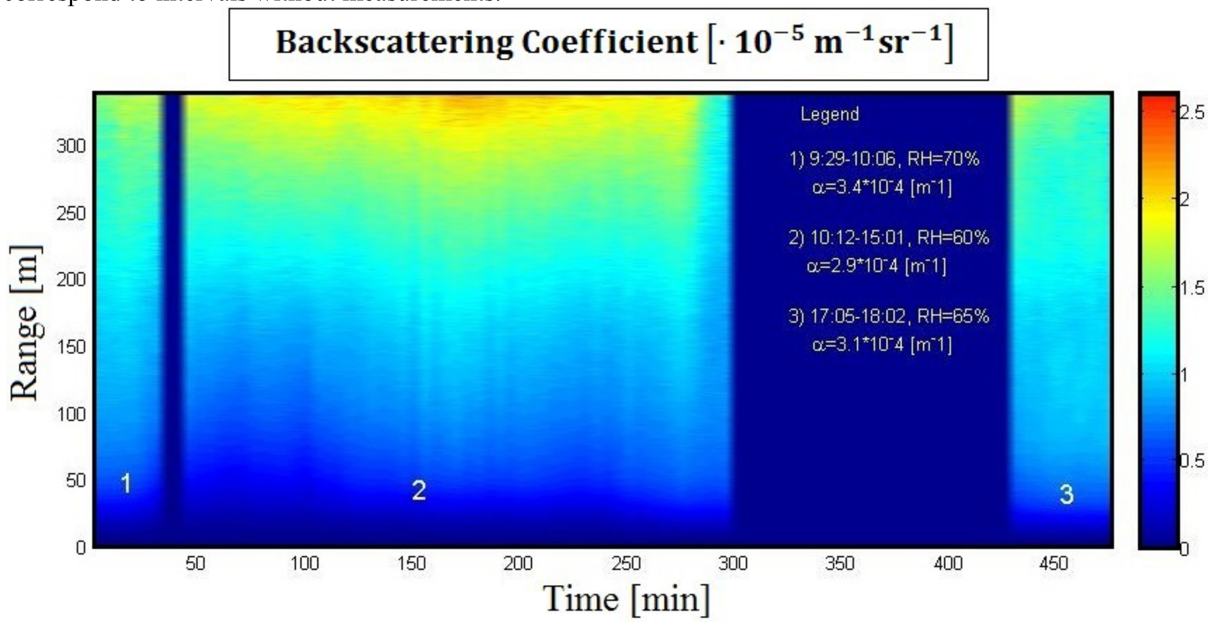

Fig 3. Variation of Mean Backscattering Coefficient with the Time. Starting time 9.29 a.m.

From the previous image, we can see that the global extinction coefficient (α) vary as a function of acquisition time. This is due to the fluctuations of the traffic intensity. In fact for a fixed λ (equal to 355 nm), the global extinction/attenuation coefficient increases in the central part of the day of measurement, while it decreases in the first hours of the morning and in the evening.

Furthermore, an in-depth analysis of Figure 3 shows that maximum values of β ($\sim 2.5\cdot 10^{-5}$ [$m^{-1}sr^{-1}$]) are localized near the second half of the roundabout (Rome city center direction) and in Oxford Street. This fact indicates slow traffic in the whole day and in particular during the rush hours.

These results are partially in line with the annual average traffic intensity of the area (statistics extrapolated by Google Earth).

The results show in Figure 3 confirming the quality and reliability of Lidar system for the monitoring/measurement of air pollutants, such as PM_{10}, and for remote sensing/atmospheric physics applications. This technique is also an efficient support to other instruments for the detection of pollutants in (highly) traffic congested urban areas.

5 The Universal Multi Event Locator (UMEL)

In this section the mathematical background, on the data mining and statistical tools used for the automatic data analysis, is provided.

In particular, the capability of UMEL to locate events in waveforms is detailed. 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) [25], a version of SVM [26] 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).

In general, let us consider S training samples$(x_1, y_1) \dots (x_S, y_S)$, $\quad y_i = f(\boldsymbol{x}_i)$ where f: R → R is the function to regress.

The regression function is given by $f^*(x) = \sum_{k=1}^{S} y_k^* H(x_k, x)$, where $H(\mathbf{x}_k, \mathbf{x})$ is a kernel function. The parameters $\gamma_k^*, k=1,\ldots,S$ are determined using the solution of a quadratic optimization problem with linear constraints and therefore the formalism of Support Vector Machines can be used. Only a subset of the parameters γ^*_k is nonzero. The data points $\mathbf{x}_k$ associated with the non-zero γ^*_k are called support vectors.

To perform regression, an insensitive zone, called *e*-tube, is defined that provides the required level of accuracy *e* to approximate a function *f(x)* by another function *f*(x)* such that the function *f(x)* is situated in the *e*-tube of *f*(x)*. The axis of the *e*-tube defines an *e*-approximation *f*(x)* of the function *f(x)*. Different combinations of kernels, e-values and the regularization parameter of the optimization allow determining several degrees of smoothing in the estimation.

In more detail, SVR uses the e-insensitive loss function or e-tube defined as:

$$|\xi|_e = \begin{cases} 0 & \text{if } |\xi| \le e \\ |\xi| - e & \text{otherwise} \end{cases} \tag{5}$$

The goal of SVR is to find the flattest function that fits the training data within the e-tube. To this end, 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. 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:

$$\begin{aligned} ESV \subseteq SV \quad \forall i \in ESV, \quad |y_i - f(x_i)| \ge e \\ ISV \subseteq SV \quad \forall i \in ISV, \quad |y_i - f(x_i)| < e \end{aligned} \tag{6}$$

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 on 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 4 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 4b), the samples around the step become ESVs. In the case of the sinusoidal function (Figure 4a), the ESVs appear at the beginning of the function and at the external points, corresponding to the maximum and the minimum of the function.

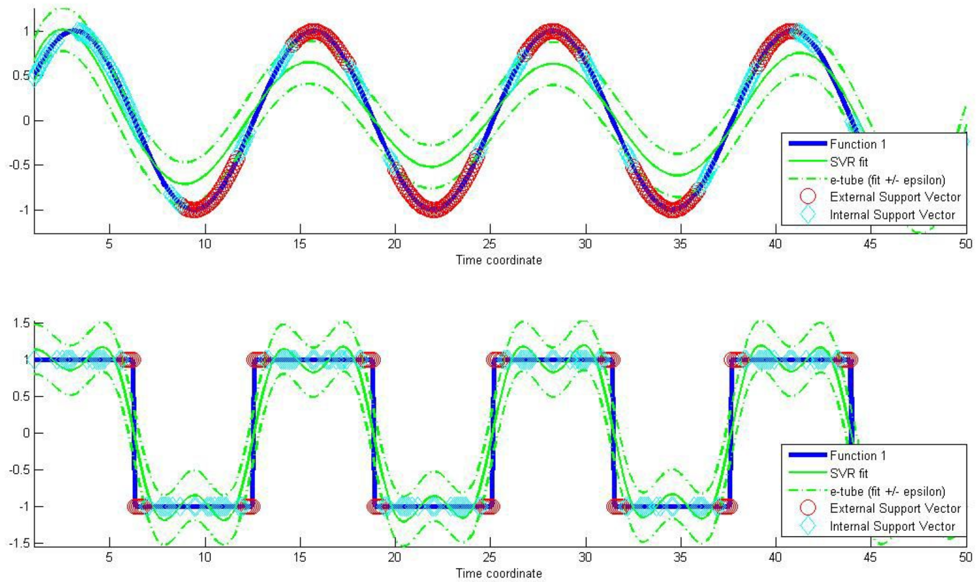

Figure 4: UMEL fit to a step and a sinusoidal function .

Most signals from measurements in the atmosphere are characterised by high frequency components in the time domain (spikes, drops, rapid slope changes, etc.). This is particularly true of Lidar measurements. Therefore, it is possible to apply UMEL to locate these events. All the mathematical details about UMEL can be found in [14].

6 Application of the Universal Multi Event Locator to Automatic detection of dangerous levels of particulate

The approach adopted for the deployment of UMEL, in the present application, is based on an appropriate choice of the e-tube for the analysis of the backscattering coefficient. Indeed, by properly selecting this parameter, it is possible to obtain external support vectors only in presence of significant levels of particulate. During the periods of the day, in which the traffic is low and there is no much emission, the e-tube is adjusted to fit the data of the backscattering coefficient using only internal support vectors. The results obtained with this approach are shown in Figures 5 and 6. Figure 5 shows the UMEL fit of the backscattering coefficient during the rush hour at 9.30. A significant level of external support vectors are necessary to fit the data in the region of high traffic, starting from about 150 meters from the location of the system. The same measurements performed at 18.45 with low traffic, and analysed with exactly the same UMEL parameters, do not present any ESV. With the proposed method it is therefore immediate to discriminate intervals during which the emission is high from periods of low emission.

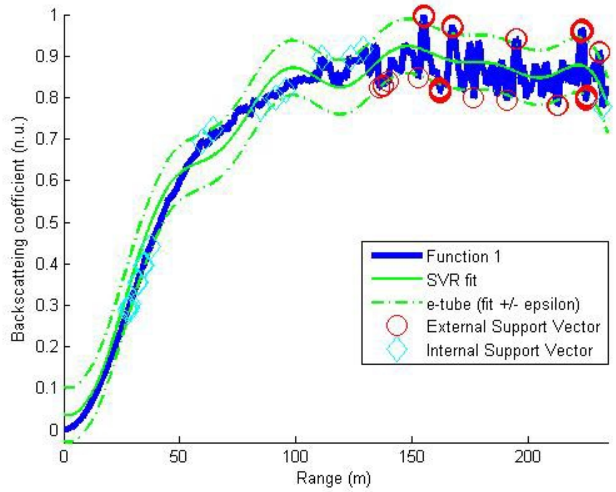

Figure 5: Example of UMEL applied to a backscattering coefficient: measurements taken at 9.30 .

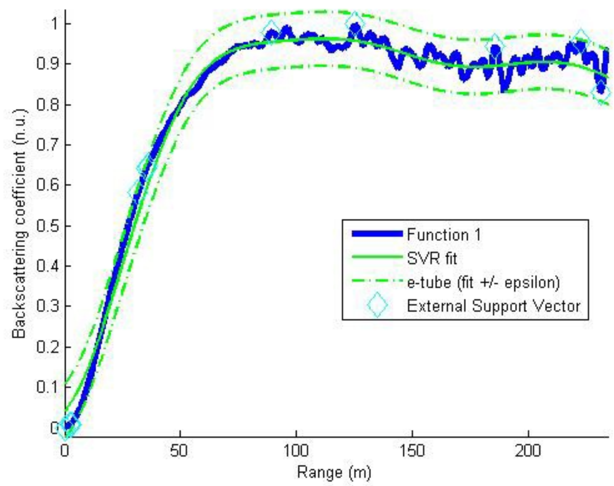

Figure 6: Example of UMEL applied to a backscattering coefficient: measurements taken at 18.45

7 Conclusions and future developments

The principal objective of this work is the study of the evolution of particulate emission in strongly congested urban areas. It is possible to perform a detailed analysis of the most sensitive parameter to describe this aspect, using active sensing Lidar techniques. In fact, the backscattering coefficient – $\beta(\lambda,R)$ [$m^{-1}sr^{-1}$] indicates the attenuation of radiation caused by scattering (at angles from 90° to 180). A specific measurement campaign, performed near the University of Tor Vergata in Rome, has clearly shown the potential of this approach to monitor the particulate emitted by strong and congested traffic. The data have been interpreted with an innovative, automatic data analysis tool UMEL. With this approach, daily aerosol concentration cycles have been clearly detected with a peak in aerosol concentration during the morning rush hours and daily plateau.

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