

# Multiparametric Characterization of Atmospheric Particulate in a Heavy-Polluted Area of South Italy

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## Abstract

To obtain a real-time image of atmospheric particulate matter (PM) in highly polluted areas and to understand how the anthropogenic component linked to urban activities (industrial activities, domestic heating, road traffic, waste disposal) can locally affect near-surface measurement of PM, several measurement campaigns were achieved in the Campania region (Southern Italy) using both Lidar and *in-situ* instruments. A comparison between the obtained results highlights a good correlation between the data and the potential of remote sensing instruments for air quality monitoring. Data analysis was performed in terms of particle backscattering coefficient profile at 355 nm, PM mass concentration, and size distribution. Wind profiles, which covered a range of altitudes from 40 m to 290 m, were also used to study sources and physical processes involved. Measurement carried out in a rural area with a landfill site highlighted the presence of a homogeneous particulate layer throughout the sounded area due to winds driving aerosol from the landfill to the surrounding areas. The size distribution in mass concentration, highlighted a modal diameter moving towards 0.9 and 2  $\mu\text{m}$  with a larger mass concentration of particles in the morning, before noon and in the afternoon when a large number of trucks delivered solid wastes. Moreover, large concentrations of particulate matter were measured in a small urban town with few industrial activities which peak ( $211 \pm 33 \mu\text{g}\cdot\text{m}^{-3}$ ) was measured in the direction of the most urbanized area, probably due to the lighting of the do-

mestic heating systems. Bimodal size distribution in number concentration was measured, indicative of two types of atmospheric particles sources: gas and liquid combustion (particles with sizes below 80 nm), including vehicular traffic and domestic gas-heating, and biomass combustion (particles with sizes of the order of 200 - 500 nm). Finally, data collected in a highly populated and industrialized area highlights the presence of particles having a high level of spherical geometry (aerosol depolarization below 5%) pointing towards the industrial area. Conversely, the measurements performed pointing toward other directions highlighted a diffused source of aspherical particles (depolarization values of about 3%) spreading throughout all city territory. The work showed as the co-location of remote sensing and near surface instruments is a promising approach to studying aerosol properties in the atmospheric layers and has more accurate information on atmospheric dynamics. Moreover, the correlation between the obtained results highlighted the potential of remote sensing instruments for air quality monitoring.

## Keywords

PM, Particle Size Distribution, Optical Particles Properties, Remote Sensing

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## 1. Introduction

Particle matter (PM) has a strong impact on the chemical and physical processes occurring in the atmosphere, affecting air quality and climate change [1]-[6]. Many studies highlighted PM's direct effect on environment, climate, natural ecosystems and human health [7] [8] [9] [10] [11] due mainly to their increased concentration. PM is generated by natural sources (*i.e.*, wind-borne dust, sea spray, volcanic ashes, biogenic aerosol), anthropogenic sources (*i.e.*, fossil fuel combustion, waste and biomass burning, industrial emissions), and photo-oxidation transformation, under sunlight irradiation, sulphates, nitrates and organic precursors that are emitted in the atmosphere from human and agricultural activities (secondary aerosol) [12]. PM is rarely homogeneous: particles vary in size and shape, chemical composition as well as successive modifications in the atmosphere that are related to the specific source and emission location. Particle size can vary from few nanometers to several tens of microns whereas the chemical composition is a complex mixture of organic and inorganic substances [13] [14]. The complexity of PM chemical composition, its wide range of size and shape, along with variations in the time, make the airborne particulate matter measurement very difficult and determining the sources a real challenge. In recent years, due to high levels of atmospheric pollution, and the considerable number of exceedances occurring for particulate matter concentration measured on the ground, several studies [15] [16] [17] were performed in a crowded area of the Campania region in Southern Italy. These studies were initiated to understand the link between atmospheric fine particulate high concentrations on the

ground and possible sources. Currently, PM monitoring is performed in different regions by designated stations under the control of the Environmental Protection Agency. These monitoring networks measure daily PM concentration near the ground, giving only a local image of the atmospheric pollution being the measurement referred to the instrument location. This means they are not able to provide information about particle sources and how these particles, once emitted and dispersed in the atmosphere, are transformed and/or transported far from the sources over long and medium distances. Differently, Lidar remote sensing devices allow the study of fine particle dynamics and observe related processes where they occur [18]. Consequently, to correlate PM time variability, measured on the ground with diffusion processes, and air masses transport phenomena, a comparison between the results derived from remote sensing and near surface instruments becomes important [19]. The identification of PM sources is a critical process for reducing uncertainty about the environmental impact of the local and central government actions. With this goal, an explorative campaign, based on the measurements of particle properties, both at the ground and in the lower atmosphere, via remote sensing, has been performed in a vast geographical area characterized by the presence of industries, waste disposal areas (landfills), vehicle traffic, and brushwood fires. This paper represents a synthesis of the study, developed by the University Federico II of Naples and the National Research Council (CNR), in cooperation with Advanced Lidar Applications s.r.l. (ALA), on airborne PM that was measured in the landfill area in S. Tammaro (Caserta) and two municipalities near Naples: S. Vitaliano and Pomigliano d'Arco. The municipalities are located between the Naples metropolitan area and the south-western part of the Caserta territory, where there are medium and small cities with strong handicrafts and agricultural activities. Combustion processes (automotive traffic, heating systems, brushwood fires, industrial plants, etc.) are among the main causes of pollution in the area under observation; they produce primary aerosol (PM and gaseous compounds) that can interact with other atmospheric components, resulting in secondary aerosol production; therefore, it is useful to characterize spatial and temporal variability of aerosol properties, classify aerosol components, and evaluate their concentration and microphysical properties, including mean size, volume, mass, number concentration and complex refractive index. To do this, the capabilities of a combined approach of active remote sensing and ground based in situ instrumentations, able to characterize different features of the airborne PM, have been used. The aim of this research activity is to study the atmospheric PM properties in an area (the Land of Fires, a huge area between the Naples and Caserta provinces) containing highly polluted sites where the seriousness and complexity of the air quality situation lead to the need for a program of continuous monitoring. This kind of analysis is noteworthy for obtaining an exhaustive picture of vertical end temporal distribution of atmospheric pollutants and the mechanisms that determine their diffusion on a local scale.

## 2. Methods

Data collected during the measurement campaigns have been obtained with sensors based on different physical principles and mode operation. Daily mass concentration of PM<sub>10</sub> has been measured using traditional gravimetric sensors. The distribution of the particle size was obtained with an Electrical Low-Pressure Impactor (ELPI) able to detect particles from 7 nm up to 10 µm. A Doppler Lidar device allowed to measure wind profiles up to 200 m and a portable Lidar system was used to study the evolution of the aerosol geometrical and optical properties with high spatial (meters) and temporal (seconds) resolutions. Conventional meteorological parameters (temperature, pressure, relative humidity, wind speed, and direction) and main pollutants concentrations are routinely measured by the Campania Regional Environmental Protection Agency (ARPAC) (<https://www.arpacampania.it/>).

### 2.1. Particulate Matter Mass Concentration

Measurements of the average daily mass concentrations of PM<sub>10</sub> on the ground have been performed by an automatic outdoor station for continuous atmospheric particulate monitoring (Mod. SKYPOST PM/HV Tecora TUV n. 936/802206/A). Filter membranes (47 mm diameter), pre-weighed and pre-conditioned, are used to collect particles. Conditioning consists of a 24 h filters exposure at about 25°C and constant humidity (around 50%). Filters are automatically changed in the SKYPOST station and the electronic flow rate is continuously controlled. A ventilation and differential thermoregulated heating system allows the instrument to operate even in extreme environmental conditions. After a selected number of measuring days, filters are removed by the operator and weighed by an analytical balance, with a reading precision of 0.1 mg, to determine PM<sub>10</sub> particulate matter concentrations.

### 2.2. Size Distributions

The particle size distributions on the ground were measured by an Electrical Low Pressure Impactor (ELPI, Dekati Ltd., Kansagala, Finland). ELPI is a particle size spectrometer for real-time monitoring of aerosols; the instrument is constituted by a corona charger, a 12-stage cascade low-pressure impactor and a multichannel electrometer. The particle size range is from 30 nm to 10 µm. An extra filter stage is added to enlarge the measurement size range down to 7 nm. Thirteen collection plates are used to sample particles as divided by the impactor and a calibration procedure is used to associate particles collected on the plates to their aerodynamic size. Data are processed by the ELPI XLS4.05 software (Dekati Ltd.). To avoid particle coagulation, an overall dilution ratio of 5 is used.

### 2.3. Atmospheric Aerosol Monitoring

Laser remote sensing devices are known as Lidar, acronym of Light Detection and Ranging, represent one of the most promising survey methods for the meas-

ure of atmospheric particles properties due to their capability to provide particles distributions, optical properties and microphysical characterization with high spatial (meters) and temporal (seconds) resolution [20]. In the measurement campaigns, we used a prototype version of a Lidar device, as developed in the frame of the I-AMICA project (<http://www.i-amica.it/i-amica>). The system, called Microjuole POrtable LIdar System ( $\mu$ -POLIS), was designed and developed by ALA Advanced Lidar Applications s.r.l., spin-off company of the University of Naples Federico II and the CNR.  $\mu$ -POLIS is a compact Lidar system combining good accuracy, safety, portability, autonomy in remote use and ease of operation. All of these features make the system suitable for atmospheric pollutant observations in a more convenient way than the traditional Lidar instruments. The Lidar device works in the UV region of the electromagnetic spectrum, swivels from the vertical to the horizontal plane, and can measure the linear depolarization to identify particulate shape. The system uses a laser source in the UV range (355 nm) with 0.04 W mean optical power at 1 kHz repetition rate. The laser beam is expanded to make the system eye-safe for distances greater than 100 m. The light reflected by the target is received with a 20 cm Ritchey-Chrétien telescope and sent to the spectral selection system that is designed to detect the elastically diffused light with both parallel and perpendicular polarization, *i.e.* the P and S components of the backscattered radiation. The device is equipped with a complete software suite allowing automatic continuous measurement and data analysis. It can analyse the atmosphere from 0.2 km to 10 km. Lidar measurements were reported in terms of particles backscatter coefficient and particle depolarization profiles [20]. From the backscattering coefficients, it is possible to evaluate the particle mass concentration. Knowing the density of the particles and their effective radius, the particle concentration can be obtained, through the equation

$$c = \sigma\beta LR\rho$$

where:

$\sigma = \frac{2}{3}r_{eff}$  is the conversion factor (in meters);

$r_{eff}$  is the effective radius of the particles;

$\beta$  is the backscattering coefficient ( $\text{m}^{-1}\cdot\text{sr}^{-1}$ );

$LR$  is the Lidar Ratio (sr), for urban particles equal to 50 sr [21];

$\rho$  the density in the range (1 - 2)  $\text{g}\cdot\text{cm}^{-3}$  and for urban particle evaluated as 1.5  $\text{g}\cdot\text{cm}^{-3}$ ;

This procedure follows the methodology already applied in [22] and [23] for volcanic ash cases.

## 2.4. Wind Profiles Measurements

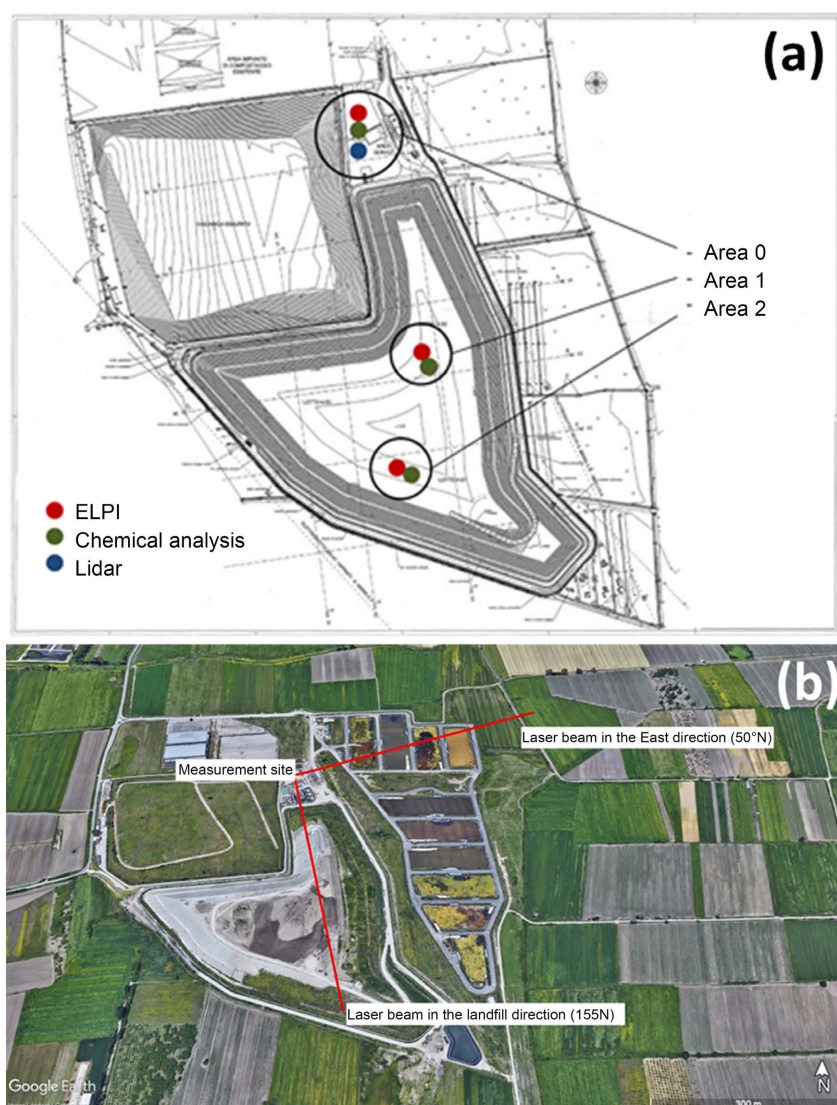
To measure wind profile, we used the Leosphere WindCube WLS7 v2, supplied by the Advanced Metrologic and Technological Services Center (CeSMA), of the University of Naples “Federico II”. The Doppler Lidar device [24], uses 200 ns

pulses of 10  $\mu\text{J}$  energy at a wavelength of 1.54  $\mu\text{m}$  and an internal GPS system. It successively sends four beams in four cardinal directions along a 28° scanning cone angle, followed by a fifth, vertical beam. This Lidar configuration allows a measure of the wind speed components and of the wind direction, in the hypothesis of homogeneous winds at fixed altitudes and a constant wind speed along the pointing directions. This Lidar device is the reference remote sensor for wind speed and direction profile measurements in the boundary layer. Wind profiles were acquired with 1-minute time resolution in order to observe processes dynamics and to have adequate information on the variability of the atmospheric circulation. Wind profiles covered a range of altitudes from 40 m to 290 m, with a 20 m spatial resolution and a sampling rate programmable between 1 s to 10 min. This allowed investigating and characterizing wind in the atmospheric layers closest to the ground.

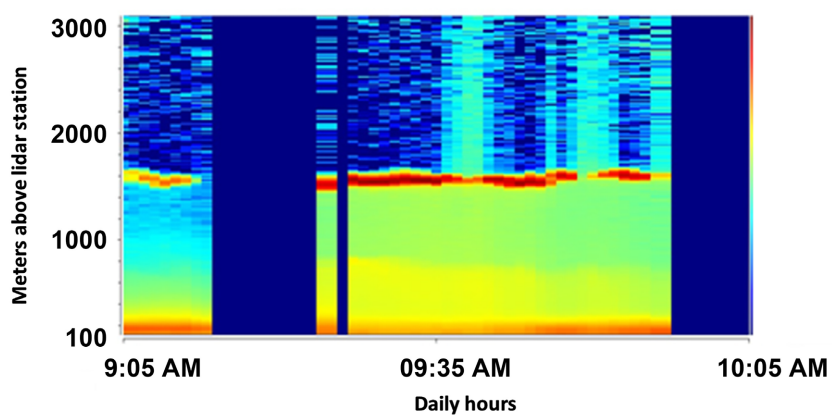
### 3. Results and Discussion

#### 3.1. Measurements in a Rural Area with a Landfill Site

To study the dynamics of atmospheric processes that strongly influence the intensity of the olfactory data, the near-surface concentration of pollutants in a landfill, and to support the creation of a sensor network allowing a sensitive and accurate analysis of the emissions, a measurement campaign using different instruments for environmental monitoring was carried out in San Tammaro, a rural area with a landfill site. Measurements were performed on 1st December 2015 and 29th March 2016 in the framework of the SIMAC (Sistema Innovativo di Monitoraggio Ambientale in Continuo) Project. Landfill particulate emissions could be caused by waste collection vehicles, special events, waste handling, wildfires or by secondary organic aerosol formation potentially caused by volatile and semi volatile organic compound emissions from landfills. Low-pressure impactor,  $\mu$ -POLIS and wind-Lidar were located on the top hill of the stored wastes and close to the management offices. **Figure 1(a)** shows the measurement site where areas 0, 1 and 2 refer to offices area, the southern and the northern zone of the landfill, respectively. Lidar measurements were carried out both along vertical direction and with an elevation of 12° in the waste disposal direction. Data were acquired with a 30 seconds temporal resolution. **Figure 2** reports time variability of zenithal Lidar measurements carried out from 09:05 AM to about 10:05 AM in S. Tammaro on 1st December 2015. The map of the logarithm of the Range Corrected Lidar Signals (LOG RCS), defined as  $RCS(z) = \log(S(z)z^2)$ , suggests the presence of an aerosol layer all over the landfill area. The signal intensity is a function of the particle concentration. The presence of particulate matter distributed all over the area could be due to the dust raised by the passage of vehicles assigned to the waste transport. Vertical profiles also show the presence of low clouds in the atmosphere at an altitude of about 1.6 km (red line in the figure). Instrument calibration was carried out by normalizing Lidar data to the average concentration measured by ELPI

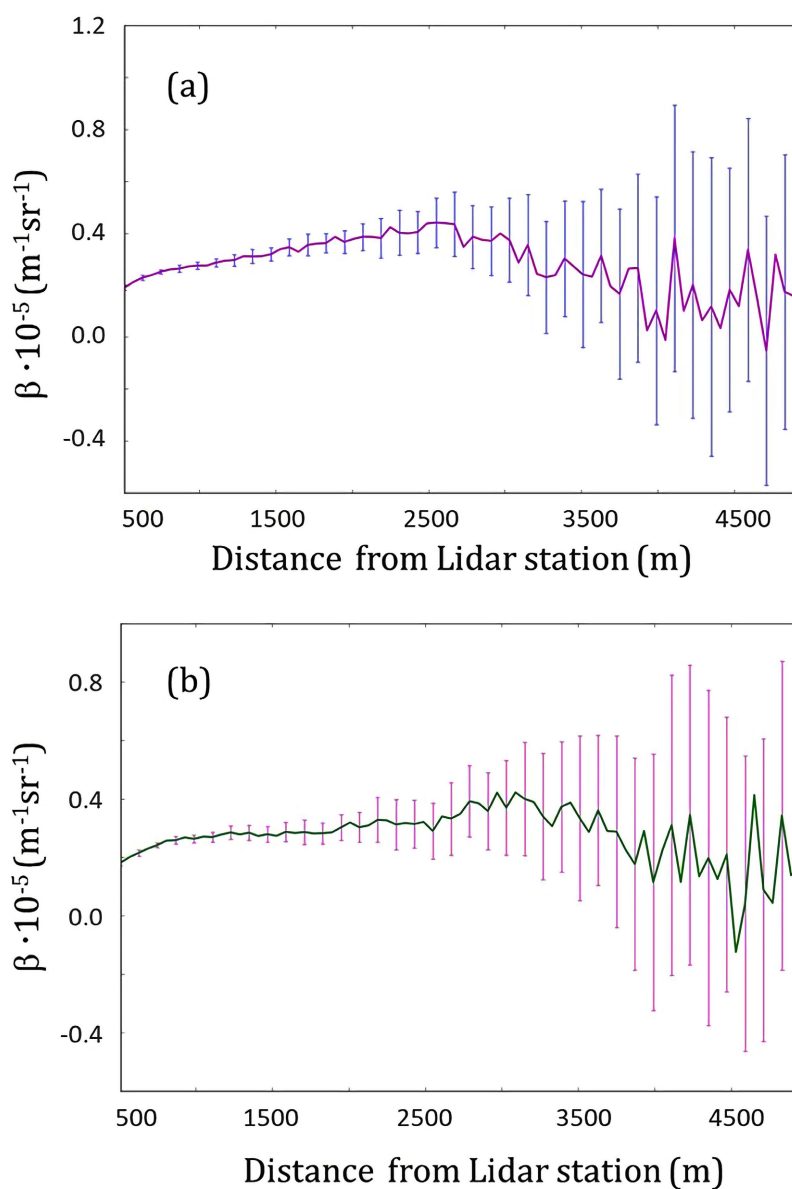


**Figure 1.** Map of the San Tammamo landfill site where are highlighted the measurement areas addressed to sampling. The areas 0, 1 and 2 refer to offices area, the southern and the northern zone of the landfill, respectively.



**Figure 2.** Time variability of the logarithmic of the Range Corrected Lidar signals at 355 nm acquired in San Tammamo on 1st December 2015.

system-placed in the same measurement area—resulted to be  $173 \pm 64 \mu\text{g}\cdot\text{m}^{-3}$ . The value of the backscattering coefficient referred to the minimum range sounded by the Lidar corresponds to an average particulate concentration equal to  $117 \pm 26 \mu\text{g}\cdot\text{m}^{-3}$  that resulted in good agreement with the ELPI data and about 4 times higher than the maximum limit established by law for the daily average. On 1st December, 2015 only few data were acquired simultaneously with  $\mu$ -Polis and with the ELPI system; however, the data resulted in good agreement ( $\gamma = 0.69$  with  $N = 20$  and  $p = 5\%$  where  $\gamma$  is the Bravais-Pearson correlation coefficient,  $N$  is the number of samples and  $p$  is the statistical significance). By extrapolating backscattering coefficient value to the ground ( $\beta = 1.21 \times 10^{-5} \text{ m}^{-1}\cdot\text{sr}^{-1}$ ) effective radius resulted  $r_{\text{eff}} = 0.28 \mu\text{m}$ . **Figure 3** shows that the backscattering coefficient



**Figure 3.** Lidar derived backscattering coefficient profiles measured (a) in the landfill direction and (b) in the East direction on 1st December 2015 in San Tammaro rural area.



profiles, obtained from horizontal Lidar measurements performed by pointing the laser towards the landfill (155°N) (a) and in the East direction (b) (50°N) (Figure 1(b)) resulted very similar. This refers to the presence of a homogeneous particulate layer throughout the sounded area. West/South-West winds (Figure 4) having a speed up to 5.9 m·s<sup>-1</sup>, could be responsible for a transport phenomenon from the landfill to the surrounding areas.

The comparison between concentrations is particularly important in the measurements of March 29, 2016. During this campaign, both remote sensing and near surface instruments were positioned in the same measurement area for the entire sampling time. This allowed us to compare a more significant amount of data. Figure 5 shows the two temporal trends indicating correlated quantities ( $\gamma = 0.68$  with  $N = 249$  and  $p < 0.5\%$  where  $\gamma$  is the Bravais-Pearson correlation coefficient,  $N$  is the number of samples and  $p$  is the statistical significance).

Figure 6 reports time variability of both measured Lidar RCS (Figure 6(a)) and aerosol depolarization profiles (Figure 6(b)). Both maps highlighted the presence of particulate below 500 m of altitude. The observed layer results are stable in time. Red spots in Figure 6(a) at altitude of about 1 km are indicative of low cloud above the measurement area. Starting at 11:00 a.m. (local time), for 2 hours, we performed almost horizontal measurements. The collected data showed an aerosol structure distant about 1 km from the observational area where the landfill linear dimensions extend for about 700 m around the measurement position.

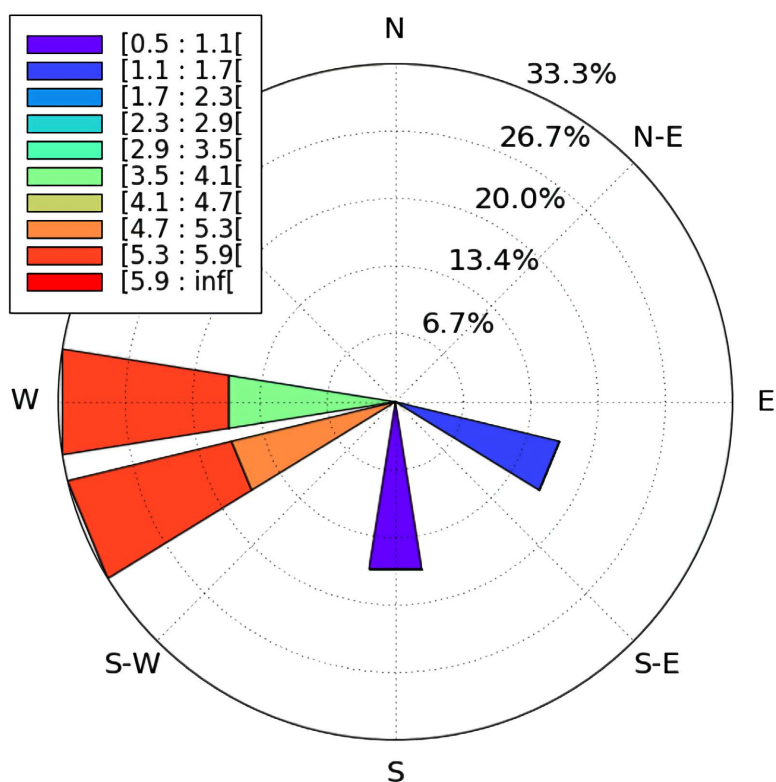
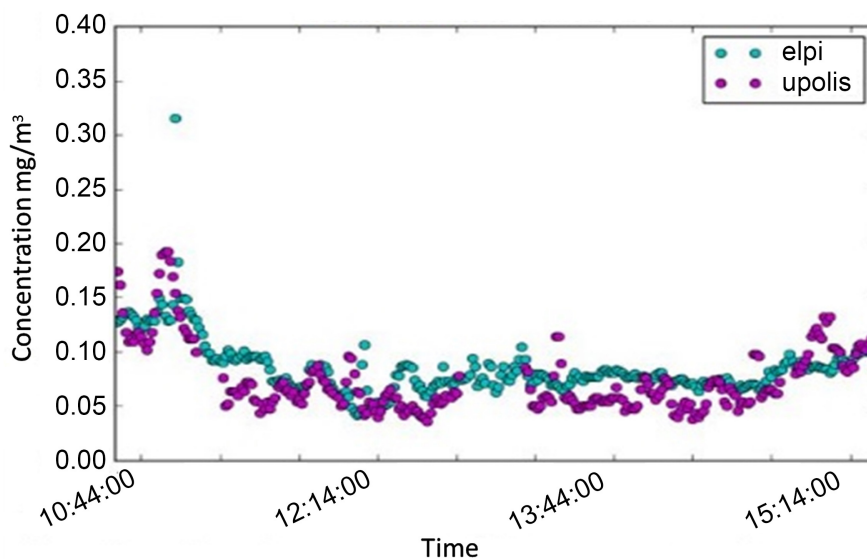
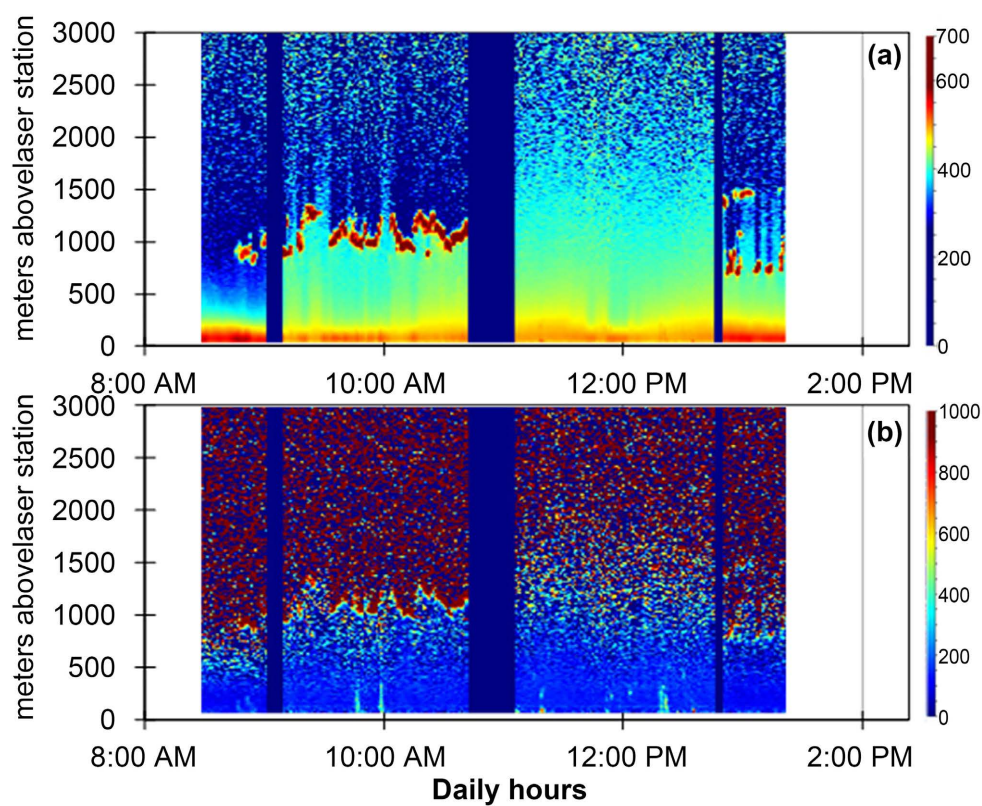


Figure 4. Wind rose corresponding to Doppler Lidar measurements performed at altitude of 40 m on 1st December 2015 in San Tammaro rural area.



**Figure 5.** Temporal trend of ELPI and  $\mu$ -POLIS measurements performed on 29 March 2016 in San Tammaro.



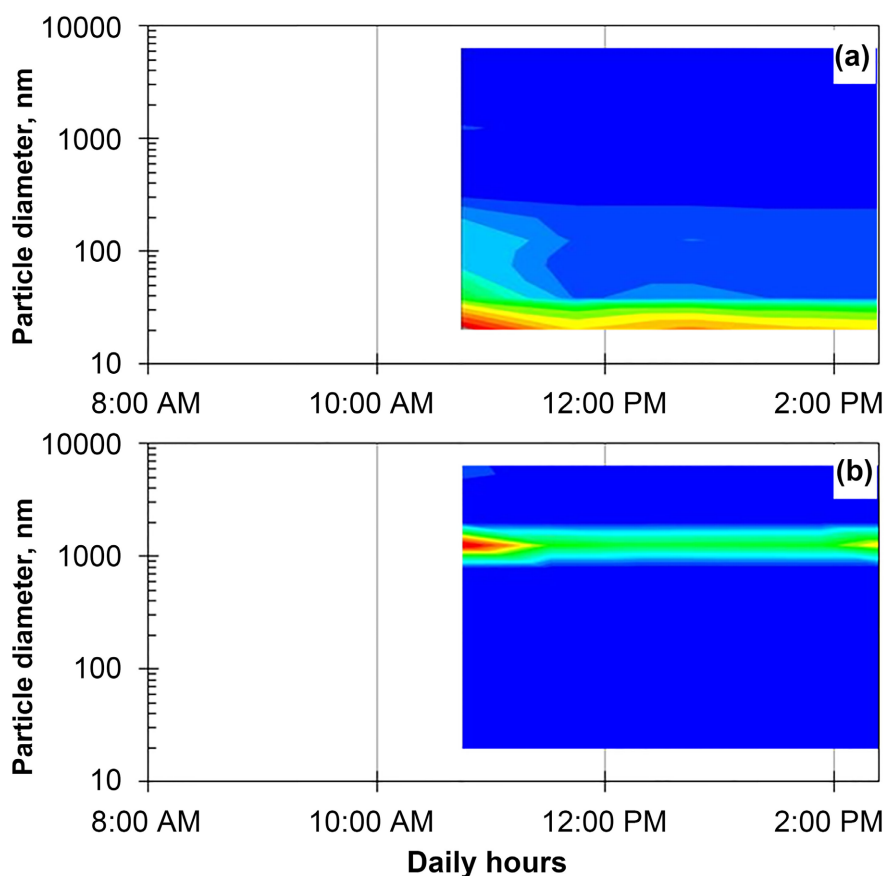
**Figure 6.** Data collected in the landfill close to San Tammaro site during 29 March 2016. The temporal range between 11:00 a.m. to 01:00 p.m. refers to horizontal measurements ( $12^\circ$  elevation), the other ranges correspond to vertical measurements (a) Log RCS of the Lidar signal at 355 nm; (b) particle depolarization at 355 nm.

Nevertheless, the particulate structure looks like it is not related to the landfill. Lidar measurements have been performed pointing an angle of  $15^\circ$  so that the

laser beam is at minimum height of 90 m with respect to the top of the landfill, at a horizontal distance of about 350 m. In this case, the Lidar signals did not show any concentration peaks, suggesting the existence of a diffused source. The temporal profiles of the aerosol depolarization showed at lower altitudes and near the surface several spots of particles having a not spherical symmetry (depolarizing particles).

Distribution in time of the aforementioned peaks corresponds to the transit of heavy-duty vehicles used for the waste discharge and/or waste handling machines. Particle size distributions are reported in **Figure 7** as color plots in number (**Figure 7(a)**) and mass (**Figure 7(b)**) concentrations. Data were measured in San Tammaro site from 10.40 to 2.00 PM and show mainly particles with diameters of the order of 20 - 50 nm. When reporting this size distribution in mass concentration, the modal diameter moves towards 0.9 and 2  $\mu\text{m}$  with a larger mass concentration of particles in the morning, before noon and in the afternoon. These two periods of the day, are characterized by the passage of a large number of trucks delivering solid wastes.

On March 29, measured wind speed resulted greater than those sampled in autumn (up to  $8 \text{ m}\cdot\text{s}^{-1}$ ) with average direction stable throughout the sampling interval with winds coming from South. In order to highlight the influence of

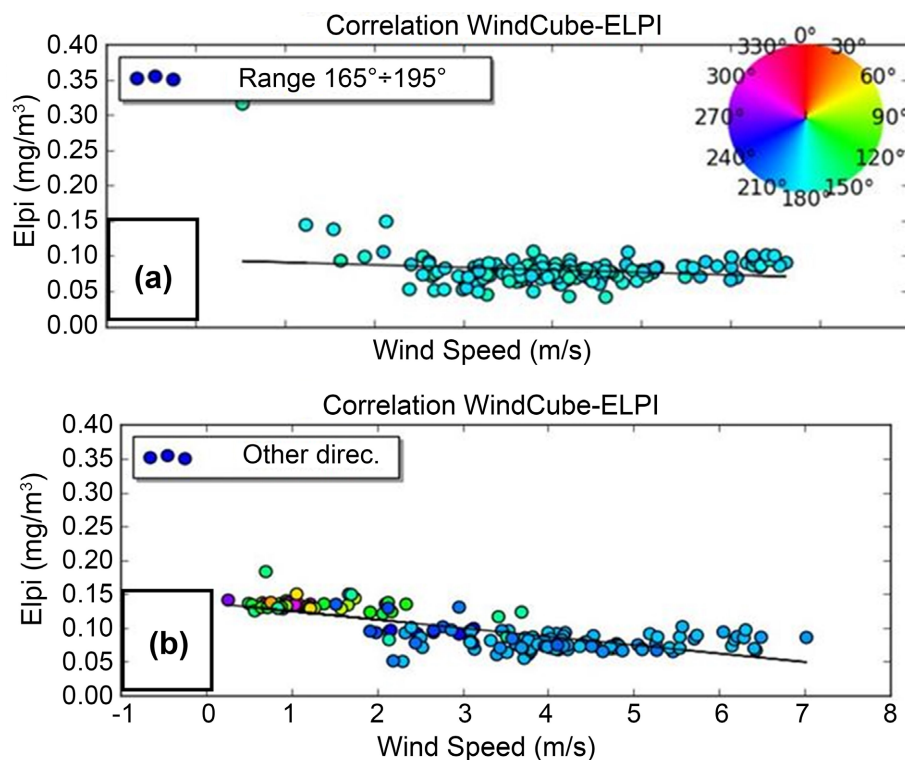


**Figure 7.** Particle size distribution measured on 29 March 2016 in S. Tammaro expressed in (a) number concentrations; (b) mass concentrations.

the landfill in the reported measurements, the correlation between the mass concentration, as measured by the ELPI, and the wind Lidar results were studied. Data corresponding to wind direction in the range  $165^\circ - 195^\circ$  are reported in a distinct plot (Figure 8(a)) with respect to data corresponding to other directions (Figure 8(b)). Results reported in the figure showed that the total mass concentration did not depend on the wind speed for wind coming from south direction; therefore, no aerosol emission come from the storage area.

### 3.2. Measuring Campaign in a Small Urban Town with Few Industrial Activities

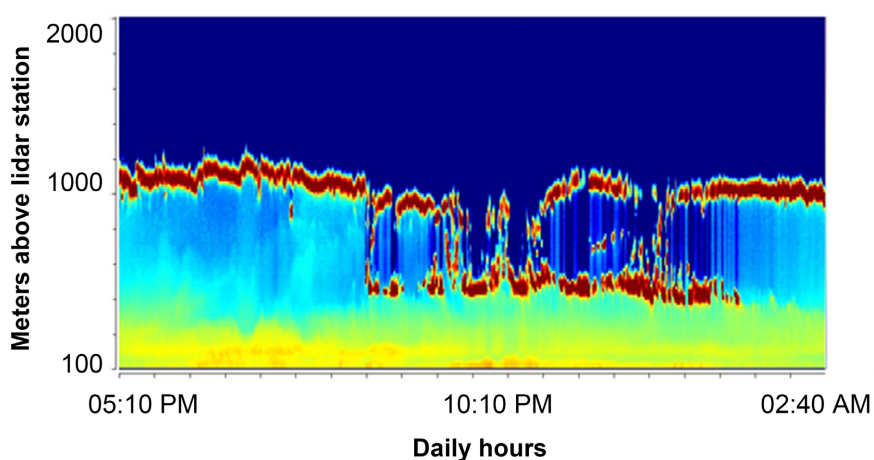
On January 28-29 2016, we performed an exploratory measurement campaign in San Vitaliano, a small, strongly urbanized town, in the city of Naples, with the goal to individuate PM sources causing the high concentrations measured on the ground by ARPAC gravimetric instruments. The gravimetric station and the low-pressure impactor were used for ground measurements whereas Lidar systems were used for wind and particulate remote sensing. The instruments were located on the roof of the city hall, in the densely populated area of the town. Both Lidar systems acquired data continuously for about 25 hours. A calibration was performed by normalizing the Lidar data to the ground concentration measured by gravimetric sensors installed by ARPAC. By extrapolating the value of the backscattering coefficient on the ground ( $\beta = 1.8 \times 10^{-5} \text{ m}^{-1} \cdot \text{sr}^{-1}$ ) and using



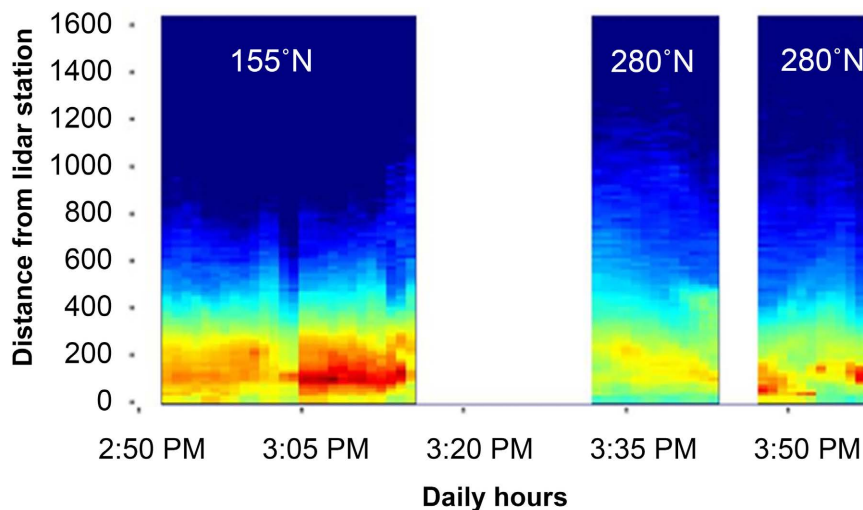
**Figure 8.** Correlation between WindCube and ELPI data for the data campaign in the landfill close to San Tammaro in 29th March 2016, (a) in wind direction in the range  $165^\circ - 195^\circ$ ; (b) in all the other directions.

the value of concentration measured by ARPAC ( $c = 224 \mu\text{g}\cdot\text{m}^{-3}$  mean value between 22:00 and 24:00 LT on 28 January), an effective radius was obtained equal to:  $r_{\text{eff}} = 0.25 \mu\text{m}$  (in agreement with diameters the modal value measured by the ELPI of  $0.6 \mu\text{m}$ ). **Figure 9** reports the color map of the time variability of the logarithmic of the Range Corrected Lidar Signals (LOG RCS), measured at the zenith from 5:10 PM. LT of 28 January to 3:00 AM LT of 29 January 2016. Vertical Lidar profiles were acquired from 100 m with a temporal resolution of 1 min and a spatial resolution of 15 m. The figure highlights large particle concentrations in the first 200 m of altitude, suggesting the presence of local PM sources especially during daytime. At night-time, particle concentration increased close to the ground, following the Planetary Boundary Layer (PBL) top height drop. A cloud layer persisting with time at the top of the PBL was also visible at about 1200 m of altitude during daytime, while at nighttime it lowered from 600 m of altitude with the PBL drop.

The scanning capability of the Lidar  $\mu$ -POLIS allowed us to perform measurements at the zenith and test the atmosphere in the near horizontal direction. In this way, we were able to achieve information on particulate spatial distribution and identify possible sources. **Figure 10** reports the color map of the time variability of the RCS logarithm, measured on 28 January. Data was obtained by pointing the laser beam horizontally and changing the pointing direction from the North area of the town, (more urbanized), to the West. Particulate layers are clearly visible in the map up to about 600 m from the measurement site. Maximum concentration, equal to  $211 \pm 33 \mu\text{g}\cdot\text{m}^{-3}$ , was recorded at 150 m from the measurement site. The peak values of PM concentration measured at about 15:15 in the direction of the most urbanized area ( $155^\circ\text{N}$ ) are probably due to the lighting of the domestic heating systems, which can be responsible for extensive and uniform distribution of pollutants throughout the area of the municipality. In the measurements performed in the morning of 29th January, a maximum concentration of  $118 \pm 55 \mu\text{g m}^{-3}$  was recorded at about 2000 m from the



**Figure 9.** Time variability of the logarithmic of the Range Corrected Lidar signals at 355 nm acquired during the San Vitaliano campaign on 28 and 29 January, 2016.

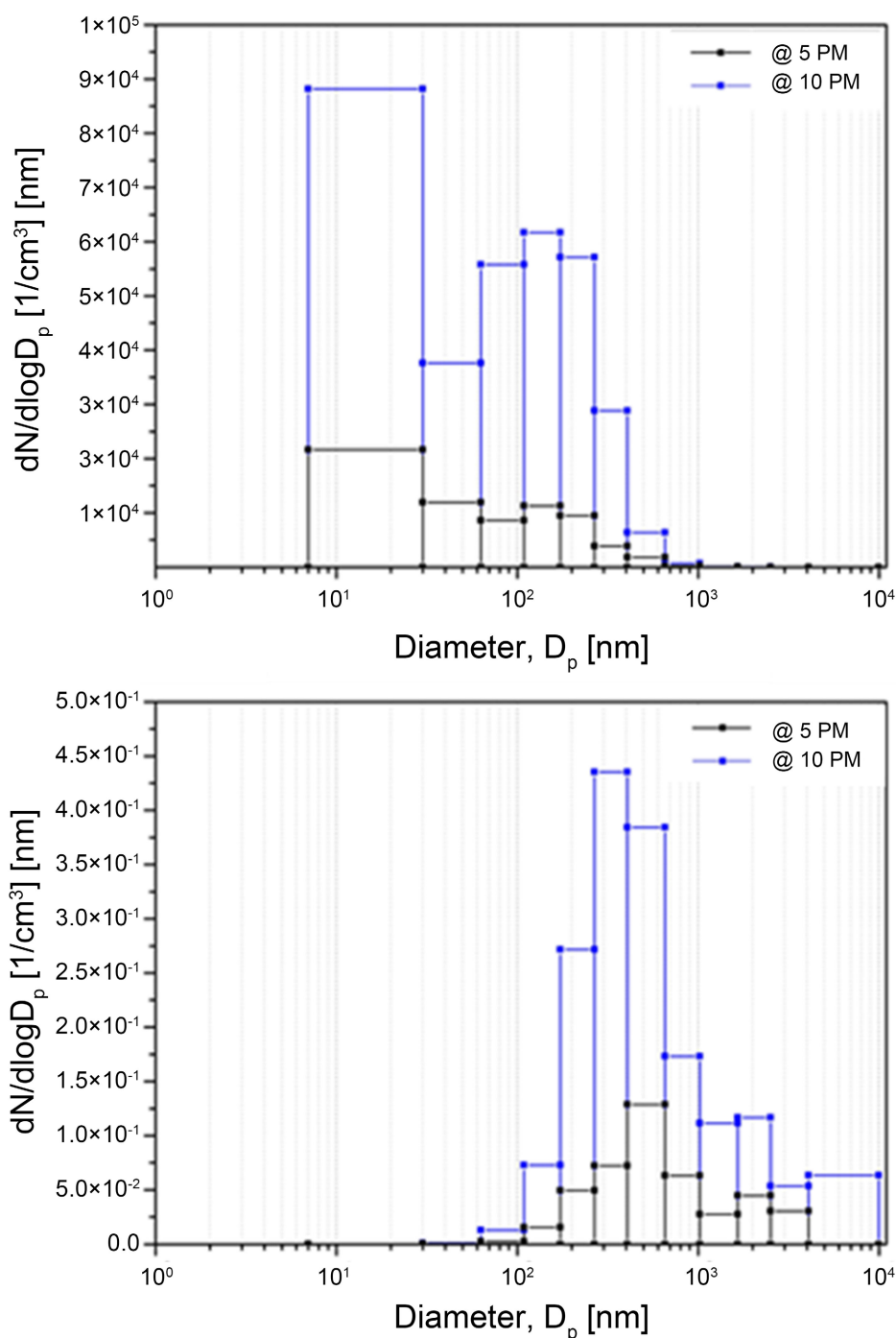


**Figure 10.** Time variability of the logarithmic of the Range Corrected Lidar signals at 355 nm acquired during the San Vitaliano campaign on 28 January, 2016. Data refers to horizontal measurements.

measurement site. This is probably due to turning off the heating systems during the nighttime and the effect of transport phenomena that removes particulate matter from the urban area and distributing it over larger distances; therefore, in the morning of January 29th, particles mixed with those related to the traffic near the municipal territory. Starting from January 28 at 9:30 AM and for 24 hours, particles concentrations were continuously measured on the ground by the gravimetric station and by ELPI.

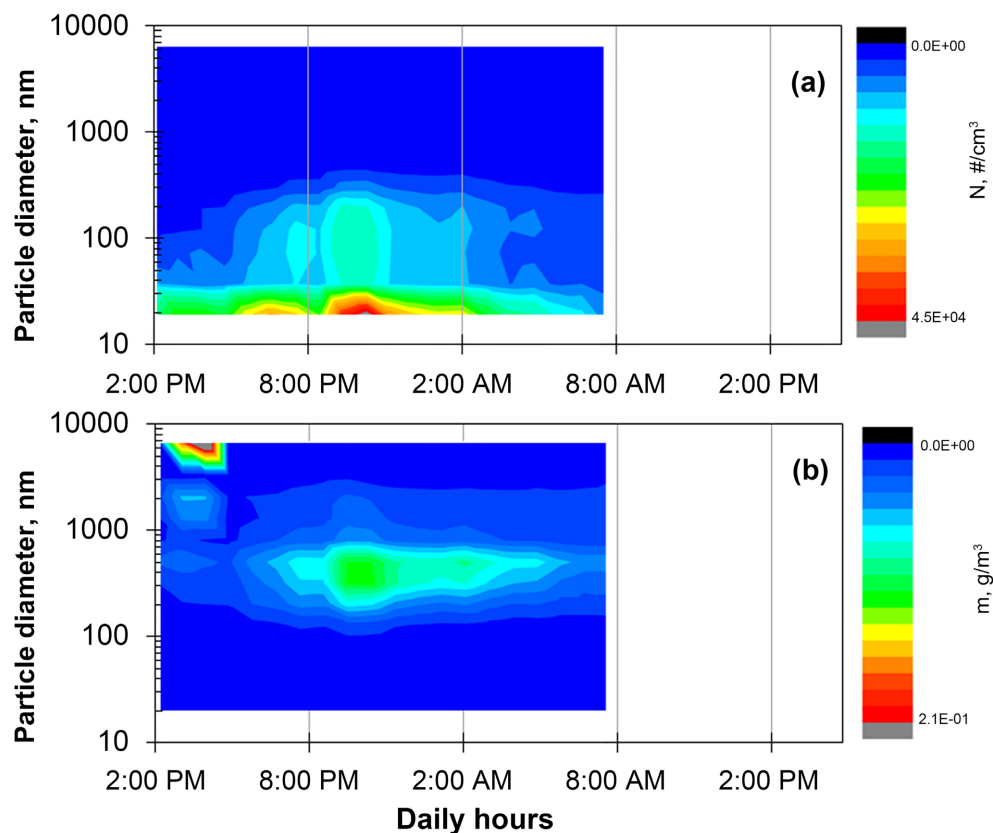
**Figure 11** reports two typical size distributions in number (a) and mass (b) concentrations measured in the afternoon (5:00 PM). Near surface particle size distributions in number concentrations (**Figure 11(a)**) is bimodal with a first mode with sizes of the order of 20 nm (probably lower size particles are also present but are not measured because the instrument limit is at 7 nm and the size is in this first stage range from 7 to 30 nm) and a second mode with sizes of the order of 200 nm.

Mass concentrations distribution (**Figure 11(a)**) is instead monomodal with average sizes of about 0.4 - 0.5  $\mu\text{m}$  although a second mode at about 2  $\mu\text{m}$  in the afternoon and 9  $\mu\text{m}$  in the night can be seen from the mass concentration distributions. The bimodal size distribution in number concentration is indicative of two types of atmospheric particles sources: gas and liquid combustion (particles with sizes below 80 nm), including vehicular traffic and domestic gas-heating, and biomass combustion (particles with sizes of the order of 200 - 500 nm) [25] [26]. These two modes in the size distribution are clearly evident if the number concentrations are measured, vice-versa they are not evidenced in the mass concentration size distribution in which sub-80 nm particles are not observed (the mass concentration is weighed on the third power of the particle sizes). Size distributions in mass concentrations evidence the mode at 2 - 9  $\mu\text{m}$  deriving from soil erosion or agricultural activities. Color plots of size distributions measured



**Figure 11.** Typical particle size distributions measured in San Vitaliano town in the afternoon and during the night (data are averaged on 60 min). The distributions are reported in a logarithmic scale in terms of: (a) Number concentrations; (b) Mass concentrations.

by ELPI are reported in **Figure 12** in number (a) and mass (b) concentrations on the same time scale interval of the Lidar measurements. The size distributions in **Figure 12** are a typical example of the measurements acquired during the entire campaign. The distributions in number concentrations (**Figure 12(a)**) show a bimodal shape with a first mode with sizes of the order of 20 - 40 nm and a

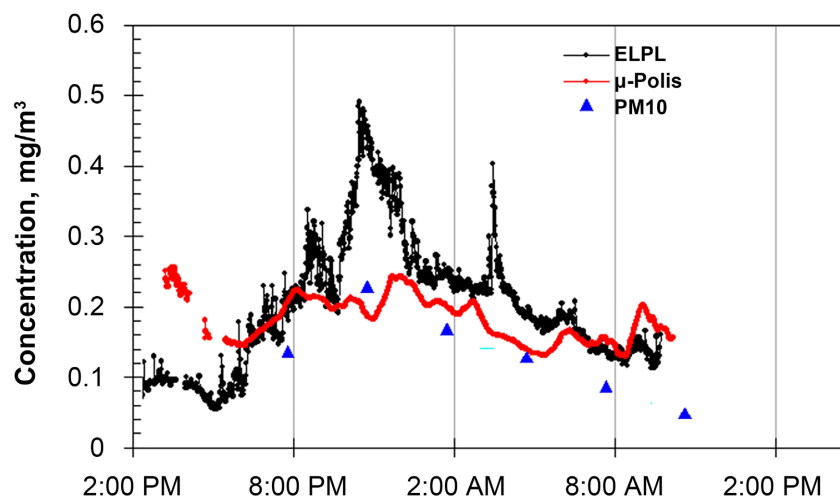


**Figure 12.** Particle size distributions measured in San Vitaliano town on 28 January 2016. The distributions are reported in a logarithmic scale in terms of: (a) Number concentrations; (b) Mass concentrations.

second mode extending down to 200 - 300 nm, particularly evident in the evening. Mass concentrations size distribution (**Figure 12(b)**) is mainly monomodal with average sizes of about 0.5  $\mu\text{m}$ . According to Lidar observations, the maximum in PM concentrations is measured night-time in correspondence to the decrease of the top height of the PBL.

San Vitaliano PM main sources appear to be domestic biomass combustion and automotive traffic. The 2 - 9  $\mu\text{m}$  peak values are indicative of large particles deriving from mechanical processes corresponding to the street cleaning following the city market on the 29 January 2016.  $\mu$ -POLIS data (at 200 m, zenith direction) were compared with both the ELPI and the gravimetric data (the last ones being measured by the ARPAC). The comparison is reported in **Figure 13** and shows a good agreement among the different data sources. It is worth to remind that Lidar and ELPI data are time-resolved with a resolution time of few seconds whereas the ARPAC data are averaged within three hours. Moreover, the Lidar data are obtained from vertical pointing measurements with extrapolation on the ground. Wind measurements did not show correlations with measured concentration (not shown) not only because of the low wind speed (wind speed from 2 to 4  $\text{m}\cdot\text{s}^{-1}$ ), but also because the particulate sources are distributed in a large area.





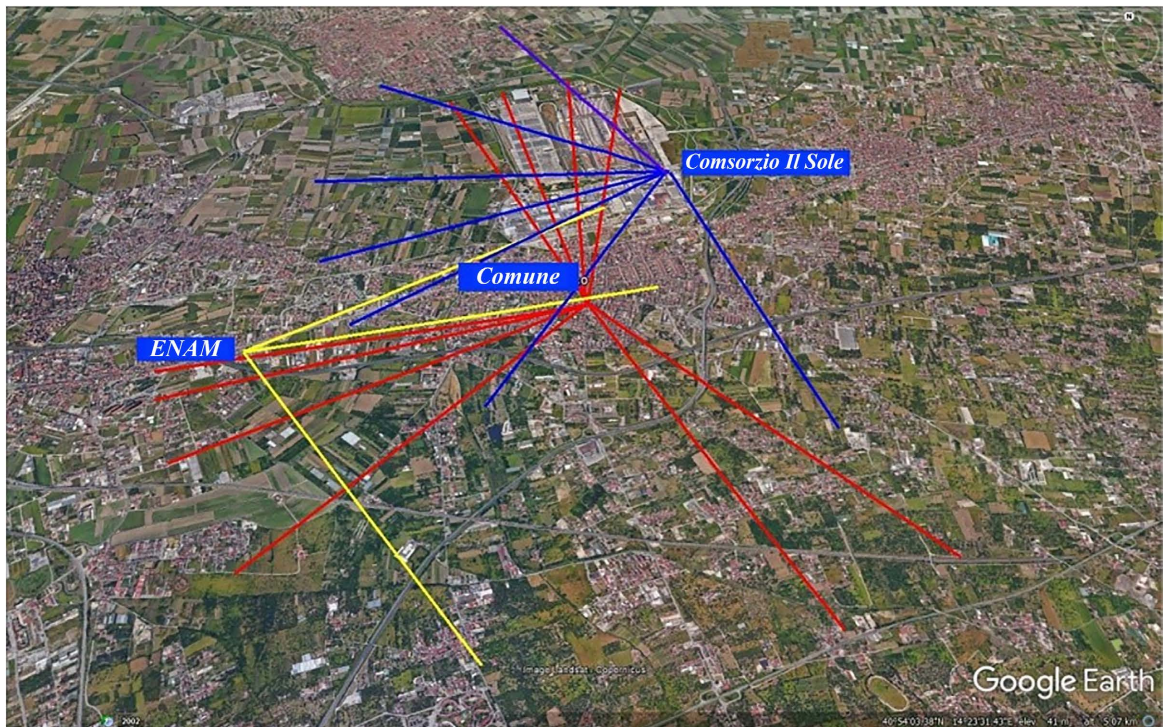
**Figure 13.** Particulate matter (PM10) measurements near surface by ELPI (black line) and ARPAC (blue points) compared with  $\mu$ -POLIS data below 200 m (red line).

### 3.3. Measurements in a Highly Populated and Industrialized Area

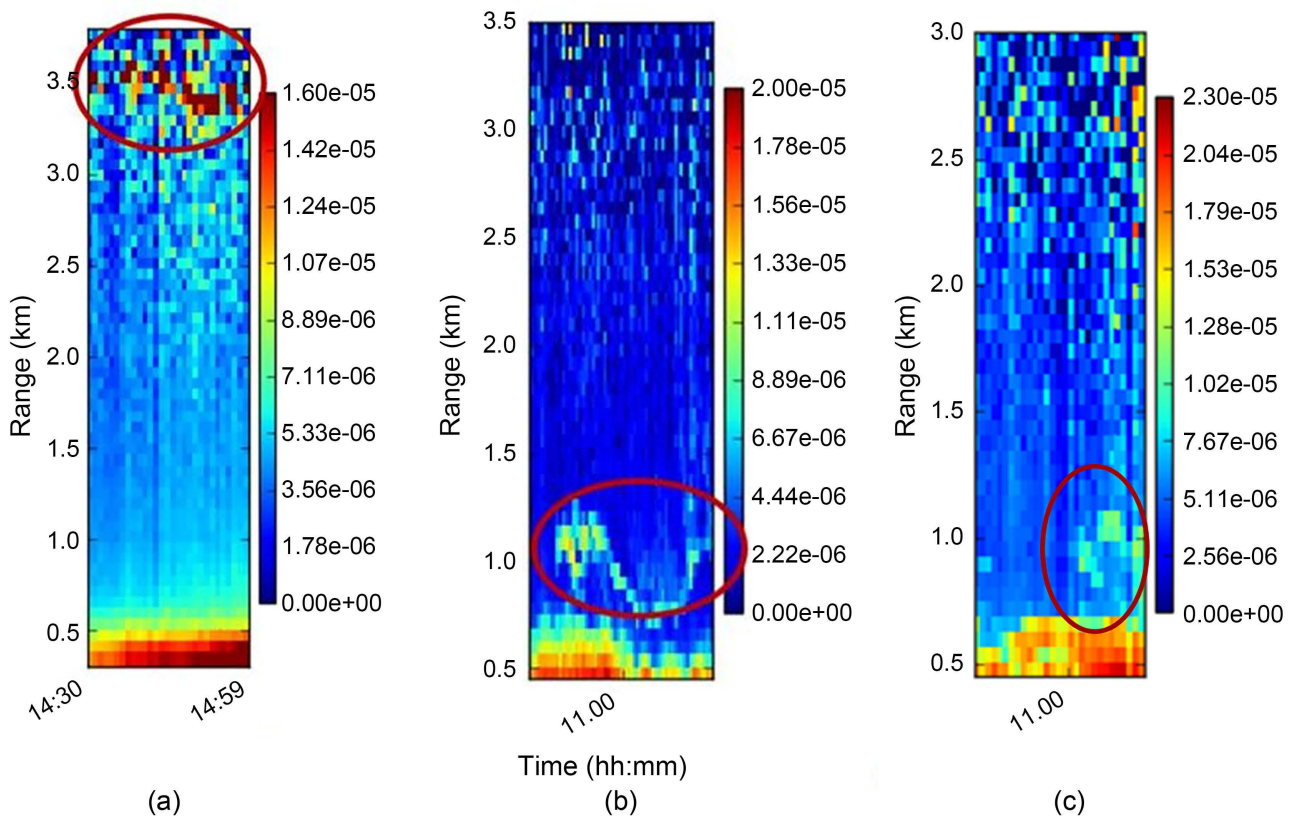
A third measurement campaign was carried out in several areas of Pomigliano D'Arco (Naples, Italy) between December 2016 and February 2017. In the present work, we will report the results from some of the horizontal and vertical measurements. The reported horizontal measurements were performed daytime on December 5, 6, and 9, 2016 by pointing the Lidar laser beam from the city center towards the industrial area, while the reported vertical ones were performed from December 7 to December 9 continuously, and during the night from December 22 to December 23.

Lidar results are expressed in terms of backscattering coefficient, with a 1-minute integration time. Data collected from Pomigliano City Hall (Comune) allowed investigating the atmosphere in the city center (a very urbanized area); from the City Hall location, we were able to perform the horizontal measurements in three different directions: the industrial area, the south-west and south-east suburbs. **Figure 14** shows both the measurement area and Lidar pointing direction, chosen in order to map the municipal area and to identify local particulate sources. We will describe here the measurements performed by pointing the laser beam towards the industrial area. Lidar data collected on December 5 by pointing the laser beam with an elevation of  $2^\circ$  highlighted the presence of an aerosol layer in the first 500 m of distance and an aerosol plume at about 3500 m (meaning 120 m high).

**Figure 15(a)** shows the backscattering profiles of the aforementioned layers. The related aerosol depolarization (mean value below 5%) highlights the presence of particles having high level of spherical geometry (water vapor) in the plume. The day after, on December 6, as reported in the color maps of **Figure 15(b)**, Lidar-derived backscattering profiles again pointed out the presence of two particles layers. The first extending up to 600 m (70 m in altitude) and the second up to 1000 m (100 m in altitude), changing in time approaching to the



**Figure 14.** Google Earth image of the measurement area in Pomigliano d'Arco. Colored lines refer to pointing direction of the Lidar system.



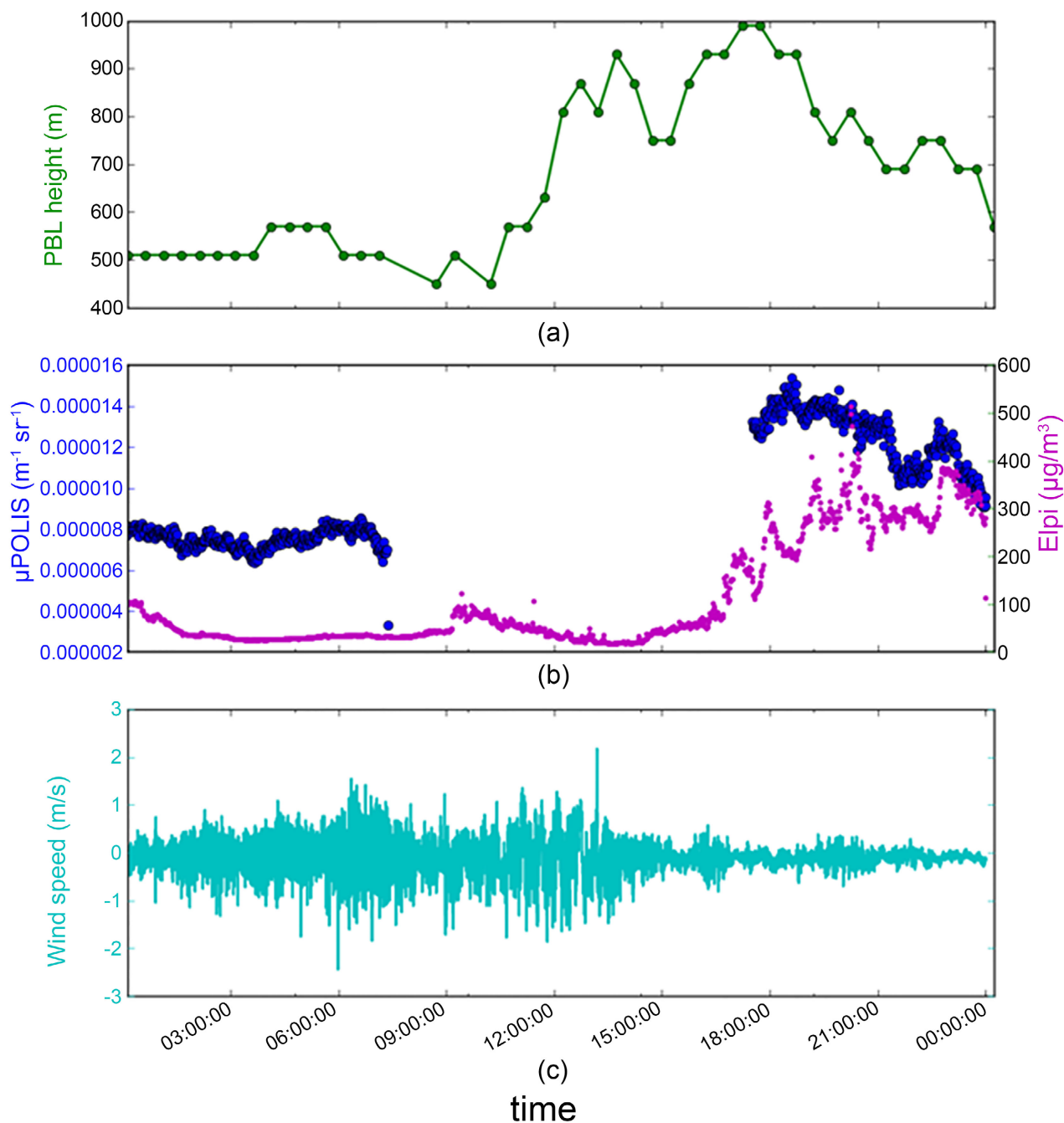
**Figure 15.** Backscattering profiles related to the data acquired in Pomigliano D'Arco town in (a) December 5, 2016; (b) December 6, 2016; (c) December 9, 2016.

measurement area. Measured depolarization values of about 3% correspond to spherical particles in both layers. The measurements performed pointing toward other directions showed a similar trend at lower altitude. On December 9, Lidar measurements highlighted an aerosol layer in the first 700 m from the observation site (with a beam elevation of 9°) and the presence of a small structure after 11 AM, at about 1 km from the site (**Figure 15(c)**). The structure seems to be compatible to the one highlighted by the measurements performed on December 6, at the same time, direction and distance. The results lead to the hypothesis of a diffused source of particulate spread throughout all city territory. Starting from the evening of December 7 and until the morning of December 9, Lidar continuously performed vertical measurements, giving the possibility to investigate the atmosphere for almost 35 hours and during a public holiday (December 8).

From these measurements, we were able to obtain information about PBL daily dynamic in order to have a direct indication on the atmospheric layer height where pollutants are confined. **Figure 16(a)** and **Figure 16(b)** show the PBL dynamic (a) and the comparison between Lidar-derived backscattering coefficient and concentration on the ground (given by ELPI) evolution (b). Lidar and ELPI data are in good accordance taking into account that Lidar data are related to measurements taken at a higher elevation than ELPI's ones. The PBL lowering causes confinement of PM whose concentration reaches the highest value during dark hours. In this case, it was also interesting to examine time variation of wind speed vertical component that allows analyzing the relationship between PBL turbulence phenomena (linked to the vertical component of wind speed) and PM concentration on the ground. The trend highlights how an increasing PM concentration occurs with the atmospheric turbulence decrease. Nighttime measurements were also performed starting from the late afternoon of December 22 and until the morning of December 23 when the instruments were allocated in the south-east suburbs of Pomigliano, near a storage of wastepaper.

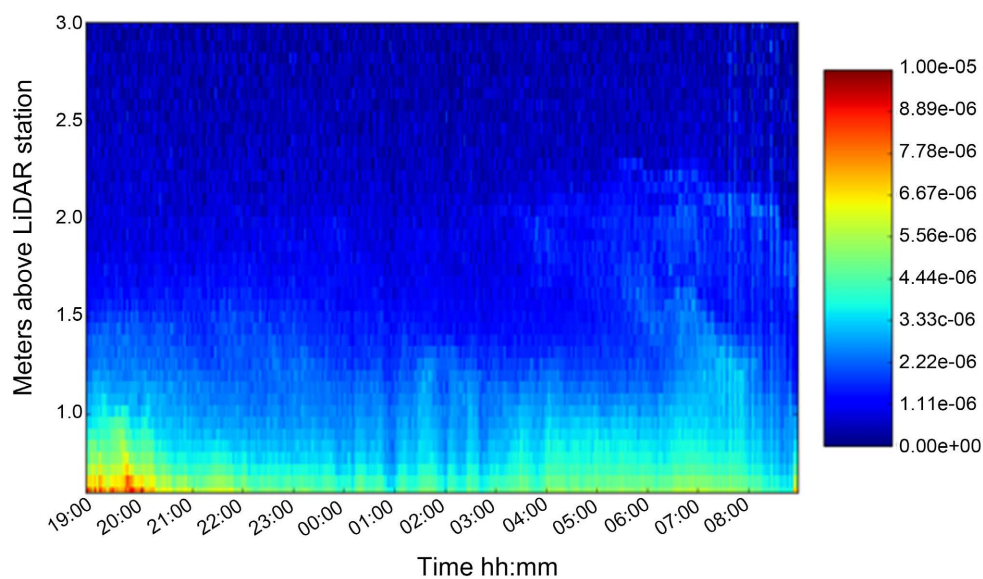
The measurements highlight an aerosol layer evolving in time and space: as shown in **Figure 17**, the backscattering coefficient value increases from the late afternoon of December 22 until the late evening with the layer extending itself up to 1 km above the ground and again an increase at 4 AM remaining almost constant until the morning on December 23. Lidar observations results from December 2016 and February 2017 highlighted the presence of extensive sources throughout the urban area of Pomigliano D'Arco and in the first 600 m from the town center. Particles concentration seems to increase at rush-hours traffic and in the evening with greater concentrations in the center rather than in town suburbs. The presence of the industrial area seems to have no relevant impact on the concentration distribution.

Particle size distributions in number concentration detected in the city center of the town of Pomigliano have a bimodal shape as clearly evident in **Figure 18(a)**. Smaller size particles (diameters in the range 20 - 30 nm) dominate the size distribution but also larger particles with sizes between 100 - 300 nm are

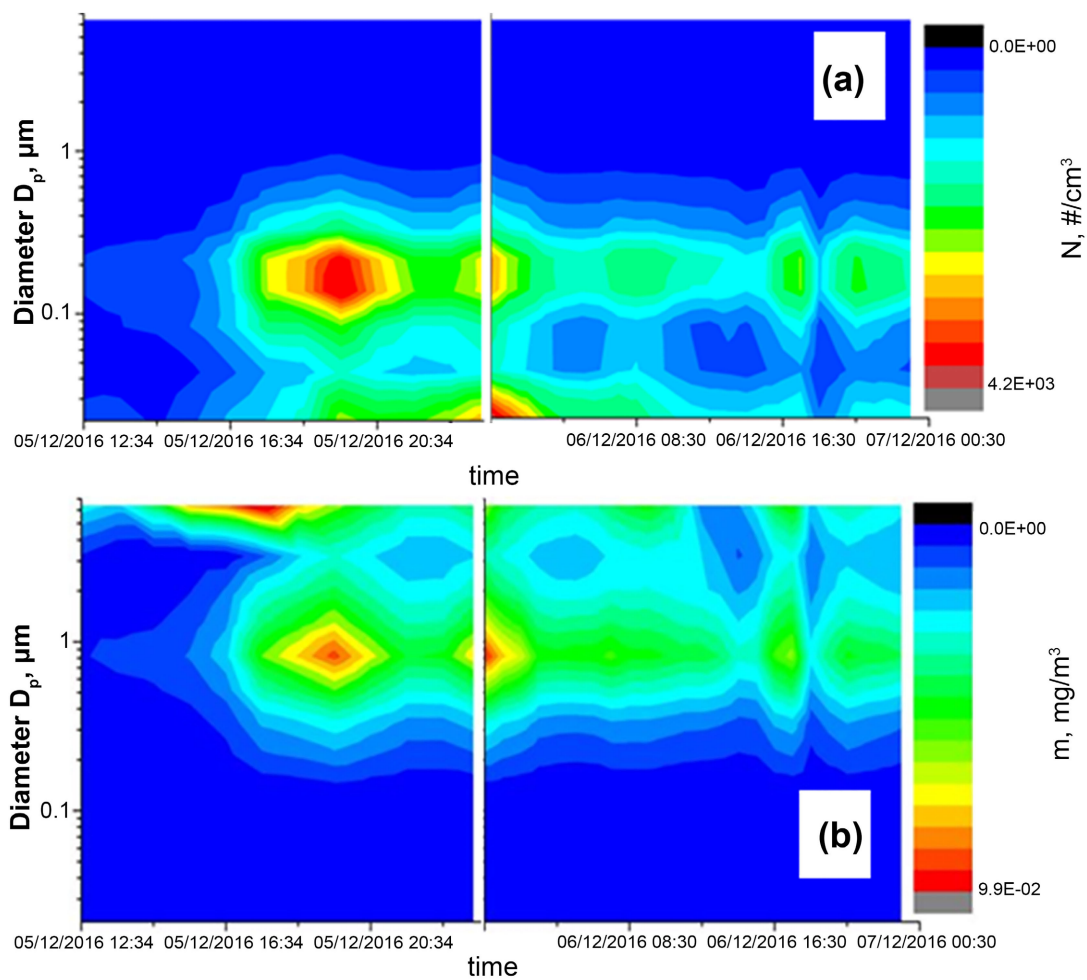


**Figure 16.** (a) Daily PBL dynamics Pomigliano d'Arco December 8; (b) Comparison between backscattering coefficient and concentration on the ground daily dynamics; (c) Time variation of wind speed vertical component.

largely present. The size distribution in mass concentration (**Figure 18(b)**) is bimodal, too. In this later case, the modal diameters are much larger, *i.e.* between 0.9 and 2  $\mu\text{m}$  and at around 10  $\mu\text{m}$ . Maximum particle concentrations are measured at the end of the day when the PBL decreases. Particle size distributions are quite different from those measured in the waste disposal. Indeed, particles have different origins. Higher concentrations are measured when wind speed lowers, but they are independent on wind direction.



**Figure 17.** Backscattering coefficient profile related to the data acquired in Pomigliano S-E suburbs starting from the evening of December 22 until the morning of December 23.



**Figure 18.** Particle size distributions measured in Pomigliano city center in (a) number concentrations and (b) mass concentrations.

## 4. Conclusions

Several measurement campaigns were performed in Campania Region of Italy by using both innovative remote sensing and near surface instruments. The campaigns had the goal to understand how and if anthropogenic sources (landfill, vehicle traffic and domestic heating), affect the airborne particulate matter values measured at the ground level. The information about total mass, main fractions, and PM size distribution was obtained by using both traditional gravimetric instruments and Electrical Low Pressure Impactor. Aerosol properties and wind profiles were studied by using an elastic portable Lidar and a Doppler Lidar; Lidars gave the possibility to obtain real time distribution of airborne particles, their geometrical and optical properties, wind speed and direction profiles with high spatial and temporal resolution. The investigation is just preliminary, although it shows how synergic use of innovative and traditional instruments can overcome the limit of the traditional method. Data provided by both Lidar systems allowed highlighting how high concentration levels of pollutants are not only near the ground but spread all over the area under investigation. Lidar measurement allowed revealing aerosol layering in the atmosphere and verifying how PBL reduction involves confinement of the particulate on the ground. The simultaneous use of both Lidar and ELPI made it possible to correlate the results coming from the two systems and determine particle effective dimensions, consistent with those deriving from combustion processes. Moreover, particle size distribution in mass and in number allowed to identify different sources of the particles at ground level. Results showed the presence of airborne pollutants homogeneously spread out in the city centers (most likely due to vehicular traffic and domestic heating) and at the same time, they allowed reducing the impact that the nearby industrial area was supposed to have. Finally, this work highlighted the capability of the measurement combined approach and showed as remote sensing instruments once tested and validated, can help to increase the knowledge about PM on the ground, paving the way for a new air quality monitoring system.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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