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Evaluation of a Commercial Aerosol Lidar Scanner for Urban Pollution Monitoring †

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Abstract: Remote sensing of particulate matter (PM) absolute concentration levels can address the need for continuous wide-area monitoring in urban environments, which arises from the adverse effects of air pollution on human health. Raymetrics PM*eye* is a unique aerosol monitoring system designed around a state-of-the-art polarization scanning UV lidar that offers large-area PM concentration monitoring and high spatial resolution source localization. The PM*eye* lidar employs a novel inversion scheme for converting raw lidar signals to PM concentrations. This study demonstrates the effectiveness and accuracy of remote monitoring PM concentration measurement results in the region of Attica, Greece. Potential synergistic use with inversion modeling techniques and dispersion models to support an advanced warning system for the population and local authorities of the Athens metropolitan area is also discussed.

Keywords: Raymetrics; PM*eye*; scanning lidar; inversion scheme; particulate matter concentrations; warnign system; Athens

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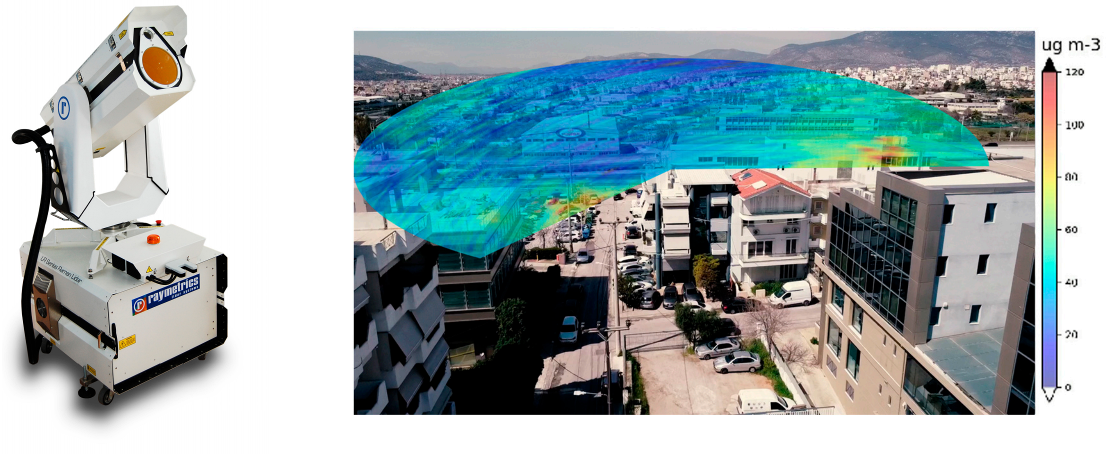
1. Introduction

Particulate matter (PM) pollution has adverse effects on human health [1], wellbeing and the economy, so accurate mapping and forecasting are considered essential to monitor and enforce air quality regulations and mitigation measures and minimize citizens' exposure to harmful conditions. Raymetrics' PM*eye* (https://raymetrics.com/pmeye/, accessesd on 4 September 2023) is a novel commercial lidar for remote sensing of PM concentrations that addresses the need for continuous wide-area monitoring. Corresponding results have been reported over two highly variable industrial sites in terms of emission sources and intensity [2,3].

The application of PM*eye* in urban environments presented in this study highlights the near-real-time, high-spatial-resolution PM concentration levels mapping that brings additional value through georeferenced localization and quantification of emission sources and emitted plumes' dispersion over the region of Attica. The accuracy and effectiveness of PM concentration remote sensing are demonstrated through a series of test case measurement results.

2. PM*eye* Lidar

PM*eye* is a state-of-the-art, eye-safe UV scanning depolarization lidar system (Figure 1a), developed by Raymetrics S.A. It emits laser pulses at 355 nm and 30 mJ at 20 Hz, has a 200 mm telescope diameter, detects both in analogue and photon counting modes and offers a 3.75 m spatial resolution of the 355.s (cross) and 355.p (parallel) components of the signals. Azimuth scanning ranges from 0° to 360°, zenith from −6° to 90°, both with 0.1° resolution. The system quality is assured using the EARLINET/ACTRIS quality assurance procedures and is designed for 24/7 unattended operation [4].



(**a**) (**b**)

Figure 1. The PM*eye* scanning lidar: (**a**) sensor; (**b**) mapping from Raymetrics premises rooftop (artistic impression based on real measurement results).

Following data acquisition, PM*eye* runs automatic data processing using a chain of processors to retrieve higher-level products (Table 1) from the raw lidar signals. The processing levels presented in Table 1 refer to basic signal processing at Levels L1a (dark correction, background subtraction and range corrected signal) and L1b (gluing, total signals and depolarization ratio), followed by Level L2, where combinations of previous level signals are used for the production of optical and microphysical quantities such as the backscatter coefficient, particle concentration, etc. Level L3 output refers to post-processing products such as frequency of occurrence maps of PM values, layer detection and classification (e.g., aerosol vs. water droplet clouds), etc. All data are available in NetCDF4 format, and their internal structure follows the Climate and Forecast (CF) convention.

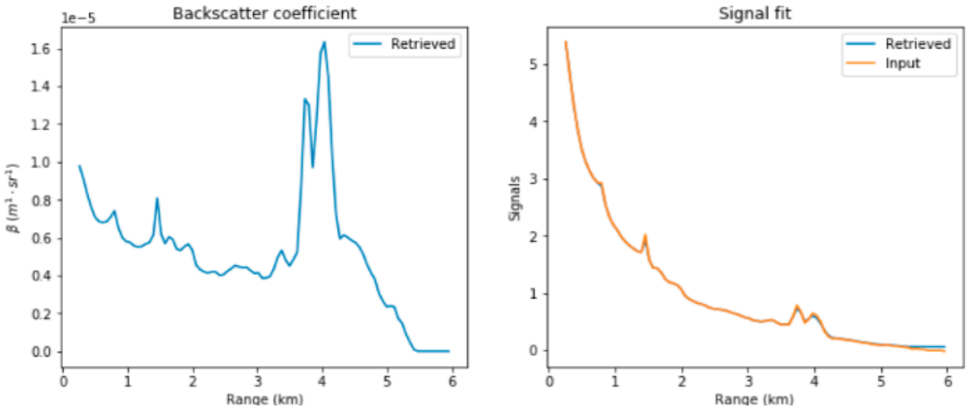
Table 1. PM*eye* lidar data processing levels and products.

Data Level	Products
Level 0	Raw lidar data
Level 1a	Pre-processed data of each lidar channel
Level 1b	Pre-processed data, gluing/averaging
Level 2	Aerosol optical properties
Level 3	Higher level products

3. PM Concentration Retrievals

A two-step approach is performed for aerosol concentration retrievals. First, a proprietary novel inversion algorithm estimates the aerosol backscatter coefficient based on raw lidar signals, treating the inversion as an optimization procedure and regularizing the solution based on physical considerations, e.g., solution smoothness (Figure 2). In this way, the inversion runs without explicit boundary conditions, as is typically required by vertical lidar inversion schemes. The second step is to derive source-specific calibration factors based on reference measurements [5], performed alongside a portable in situ PM counter sensor.

The in situ sensor used for this purpose was Dusttrak DRX 8543, TSI (Shoreview, MN, USA), which was located 2110 m, north-east from the lidar location (Figure 3). The pointing uncertainty at the distance of the sensor was estimated to be less than 30 m in range and altitude so the lidar range resolution was also averaged to 30 m to minimize collocation artifacts and achieve a better signal-to-noise ratio (SNR).



(**a**) (**b**)

Figure 2. (**a**) Retrieved optimal backscatter profile. (**b**) Comparison of the actual lidar signal (orange) with the signal that would be produced by the backscatter profile (blue).

Figure 3. Lidar (Metamorfosis) and in situ PM counter (Menidi) locations in Athens, Greece.

The intercomparison of 5 min averages of continuous measurements from 5 to 22 August 2022 are presented in Figure 4. PM*eye*'s valid range of results is from 10 μgr/m^3 up to 1000 μgr/m^3, so both sensor values, presented in Figure 4, below 10 μgr/m^3 were discarded. Lidar and in situ PM10 measurements present small deviations from each other. The mean relative difference is calculated at 7.4%, the mean absolute difference at 33.8% and the correlation (R^2) at 0.83. Results are considered satisfactory given the large distance between the two sensors, which results in reduced certainty in targeting (colocation of the lidar laser beam and in situ sensor).

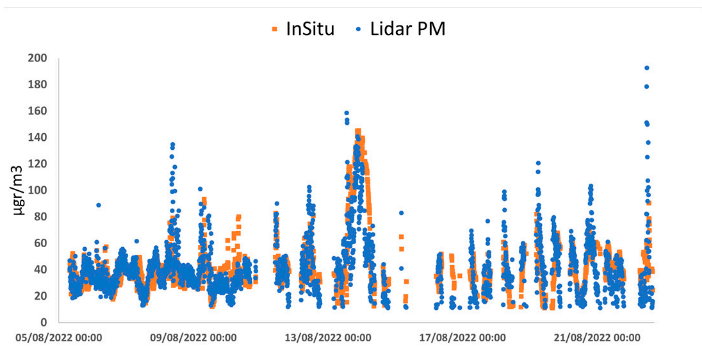
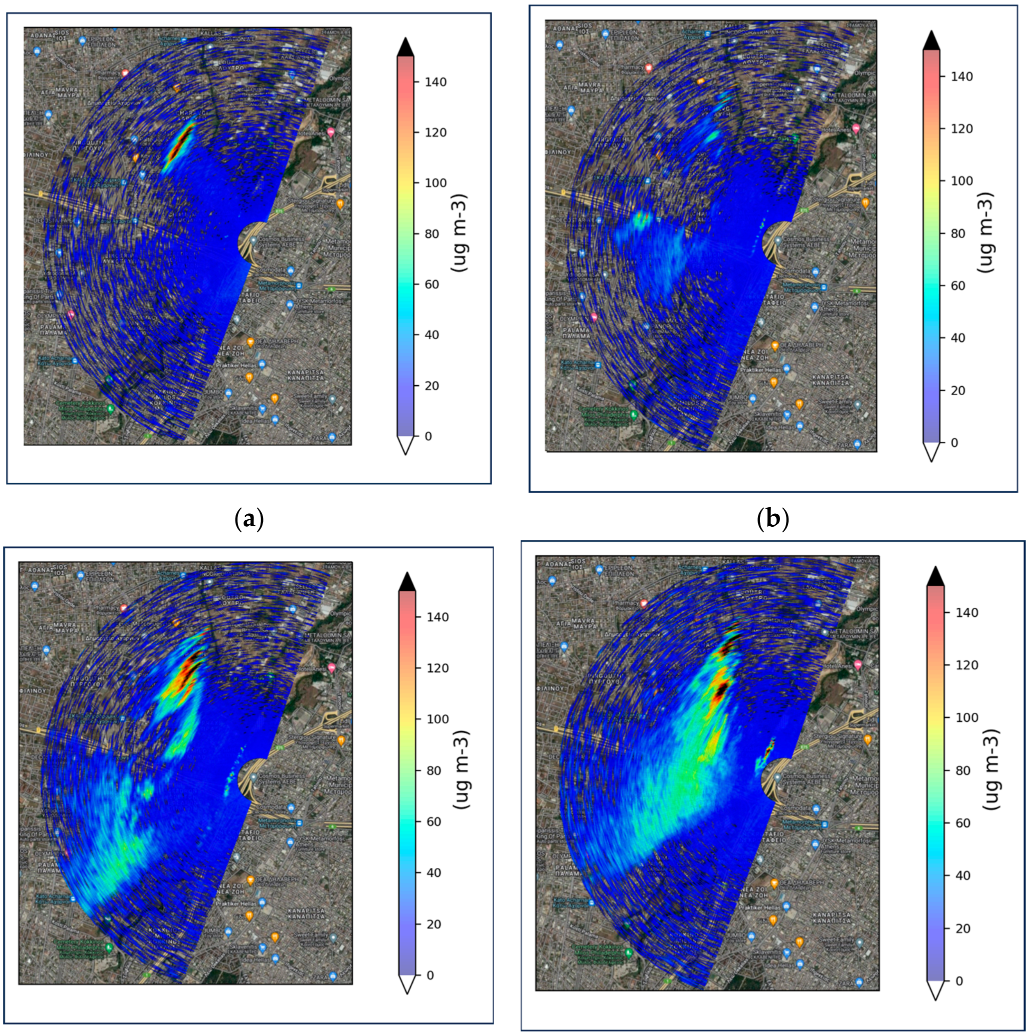


Figure 4. Lidar PM10 concentration and in situ PM sensor time series, August 2022.

4. PM Monitoring in Urban Environments

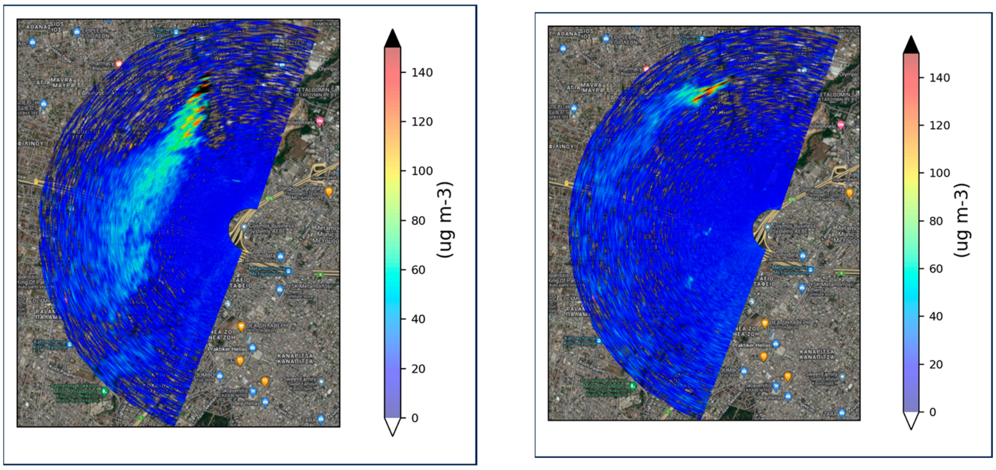
Calibrated and interpolated horizontal scanning (Figure 1b) results are presented in Figures 5 and 6. The system performed horizontal, approximately 180° range, sectoral scans using a 2.5° azimuth step with a 10 s measurement duration at each step, resulting in close to 20 min total scan durations.



(**a**) (**b**)

(**c**) (**d**)

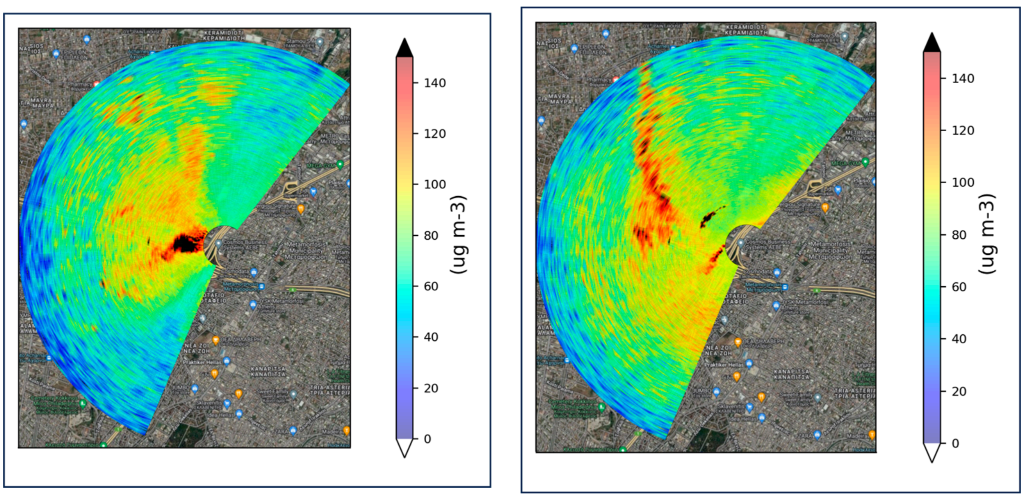
Figure 5. *Cont.*



(**e**) (**f**)

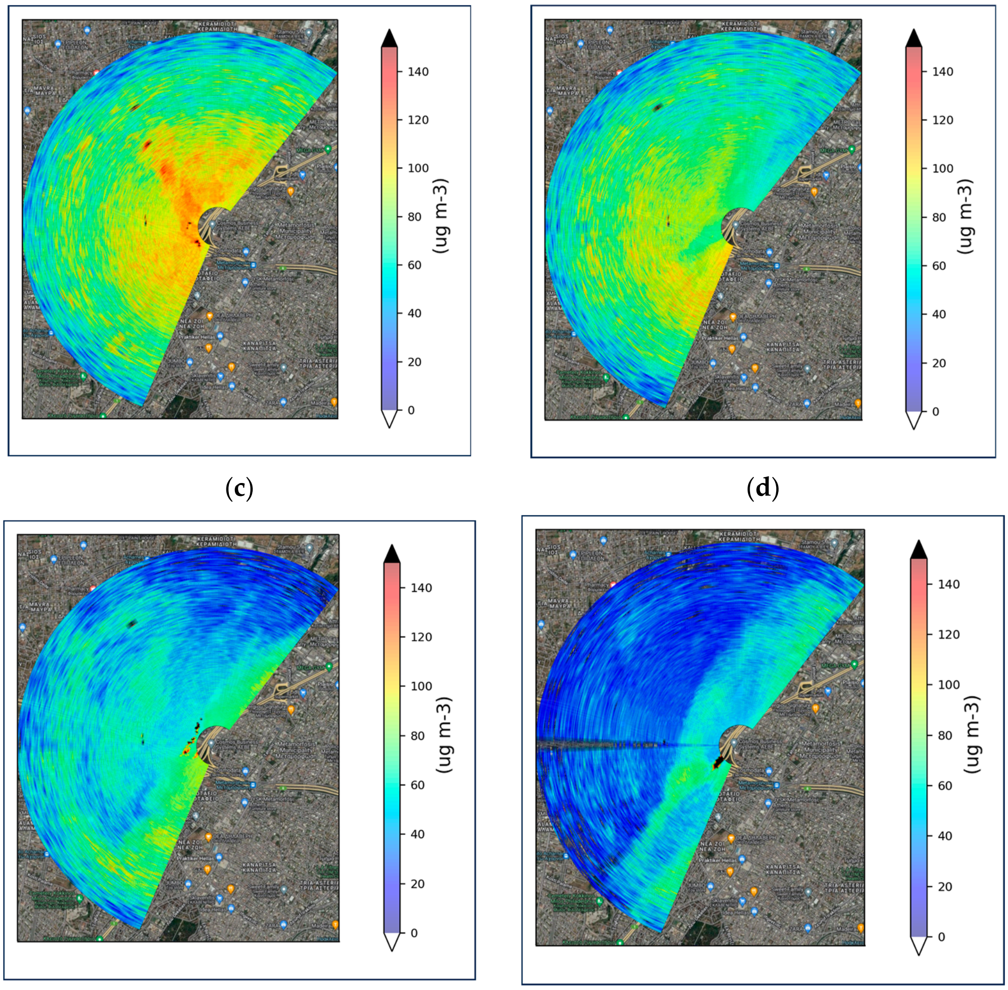
Figure 5. Lidar monitored PM10 concentrations 9 January 2022 (EEST) at 08:07 (**a**), 08:24 (**b**), 08:43 (**c**), 09:00 (**d**), 09:17 (**e**), 09:35 (**f**).

An urban fire's suspected uncontrolled tire burning, emissions and plume dispersion are presented in Figure 5, in a sequence of six (6), 17 min horizontal scans. The presented radius of PM concentration levels is 2 km, and results have been filtered for values below 10 μgr/m^3. The first PM emissions captured in Figure 5a correspond to maximum concentration levels near the source up to 341 μgr/m^3. In Figure 5b, the PM concentration is significantly reduced over the source, hence the gap in the dispersion downwind, possibly attributed to plume elevation due to buoyancy. Additional emitting sources are then monitored, with concentration levels reaching near their source at a maximum of 476 μgr/m^3 in Figure 5c and 184 μgr/m^3 in Figure 5d, where the dispersed plume shows values more than 100 μgr/m^3 several hundred meters downwind. In Figure 5e, the emission sources are decreased in number, but concentrations were locally found to reach 461 μgr/m^3. Figure 5f shows the gradual reduction of emissions and advected plumes before the termination of the incident. In both Figure 5c,d, the emissions of a less intense and localized point source, very close to the lidar, correspond to emissions from an industrial site that reaches concentrations of maximum 230 μgr/m^3. This particular source is also present in Figure 6e, while another similar industrial point source is also evident in Figure 6b, north-west of the latter.



(**a**) (**b**)

Figure 6. *Cont.*



(**c**) (**d**)

(**e**) (**f**)

Figure 6. Lidar-monitored PM10 concentrations on 20–21 March 2023 (EEST) at 21:27 (**a**), 22:09 (**b**), 23:13 (**c**), 01:01 (**d**), 01:44 (**e**), and 02:48 (**f**).

Figure 6 presents a smog event attributed to domestic wood-burning, accumulating emissions. The event picks up after 21:00 on 20 March 2023, where mean area monitored concentrations reach values around 100 μgr/m^3, while after midnight these levels are significantly reduced. Similar concentration levels have been reported in recent studies [6,7], underlining the increasing role of wood burning for heating purposes in urban pollution. The dense plume major sources seen in Figure 6b correspond to maximum values of 744 μgr/m^3, while in Figure 6a, the extended plume found next to the national highway and Attica peripheral road junction presents values up to 451 μgr/m^3 and could possibly also be related to traffic. The origin of the distinctive plume seen in Figure 6f downwind of the junction, with the highest emitted concentrations found at 449 μgr/m^3, given the time of the day, possibly suggests the existence of various additional major local sources. What is also evident in Figure 6e,f, is that dominant northwest wind directions advect pollution emitted upwind from other urban areas, contributing to the monitored area's emissions.

5. Discussion

Novel remote sensing technologies like PM*eye* offer wide area coverage, emission source localization and plume dispersion monitoring at the cost of a lower monitoring frequency compared to in situ sensors. Thus, in the case of very brief and abrupt emission events, although the dispersed plume could be monitored, the exact location of the source might not be mapped. Inversion modeling could be used for near-real-time identification of the sources and optimization of current emission rates, similar to emission estimation's bottom-up approach from satellite observations, with the difference that PM*eye* offers the distinct advantage of utilizing data very close to the sources, thus being a better proxy. Such an approach could enhance the reliability of air quality forecasting systems, which rely in general on static emission inventories that are often outdated due to fast-changing patterns in human activities, but also due to unexpected disasters such as fires or industrial accidents that cannot be predicted a priori. With a constantly updated emission source inventory, monitored area and forecasted background concentration levels, a high-resolution dispersion modeling system (e.g., building-aware Gaussian or Langrangian dispersion models) would offer realistic near future air quality predictions that could support an advanced warning system for the population and local authorities.

6. Conclusions

Raymetrics PM*eye* is a novel, state-of-the-art commercial scanning lidar system that uses an innovative inversion scheme for transforming raw signals into aerosol (PM) concentrations. PM*eye* is a unique remote sensing solution for monitoring aerosols in urban and industrial areas. Measurements performed over Attica, Greece, support the accuracy and effectiveness of the system. Measurement validation against a light scattering in situ PM counter presented high correlation and very low mean relative differences. Horizontal scanning measurement results during an urban fire incident and winter smog conditions due to wood burning underline the usefulness of the system in PM concentration monitoring (in terms of remote sensing), source quantification and localization. An agile urban-scale forecasting system for air quality in the near future is suggested that could benefit from utilizing the concentration levels monitored by PM*eye* through inversion techniques and dispersion modeling.

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