Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIV, 2025
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

# ADVANCING URBAN AIR POLLUTION MONITORING WITH REMOTE SENSING AND LOW-COST SENSOR TECHNOLOGIES

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***Abstract***

*Urban air pollution poses a critical challenge due to rapid urbanization, increasing vehicular emissions, industrial activities, and infrastructure expansion. Accurately assessing pollution levels and pinpointing emission sources is essential for effective environmental management. This study integrates advanced remote sensing techniques with cost-effective sensor technologies to monitor air quality in an urban setting. Mobile measurements were conducted on April 18, 2024, using the UGAL MDOAS system and the Sniffer 4D sensor, both mounted on a vehicle. The UGAL MDOAS system employs Differential Optical Absorption Spectroscopy (DOAS) to detect atmospheric trace gases, while the Sniffer 4D utilizes electrochemical sensors to quantify pollutant concentrations. This study focuses on measuring and comparing $NO_2$, $O_3$, $SO_2$, O4 and PM levels from both instruments. The findings contribute to enhancing urban air pollution monitoring by demonstrating the effectiveness of hybrid measurement approaches in identifying pollution hotspots and improving air quality assessments.*

***Key words****: air pollution, urban monitoring, remote sensing, low-cost sensors, DOAS, air quality assessment.*

## INTRODUCTION

In recent years, the increase in air pollution in urban areas has become a significant problem. The development and expansion of rural areas comes at the same time as increasing pollution and decreasing the quality of the environment in which we live. It affects the health of residents, causing everything from respiratory discomfort to chronic lung and even heart diseases (Adebayo-Ojo et al., 2022.; Bernstein et al., 2004; Brunekreef et al., 2022; Zhang et al., 2014). Among these dangerous pollutants are $NO_2$, $O_3$, $SO_2$ and particulate matter (PM) (Adebayo-Ojo et al., 2022; Al-Janabi et al., 2021). In addition to negative effects on human health in their primary state, these pollutants can transform, with the help of other substances in the air or ultraviolet radiation, into other much more dangerous pollutants such as photochemical smog, which has represented and represents a major problem in heavily industrialized rural areas with increased traffic (Rani et al., 2011; Tiao et al., 1975; Carlos Meier et al., 2017; D. Constantin et al., 2013; Constantin et al., 2020).

The main sources of these pollutants are industrialization, infrastructure development and expansion of urban areas as well as the increased number of vehicles, but there can also be natural sources such as fires, lightning or volcanic eruptions and even biological sources like microbial activity in soil. Advancing technology offers us increasingly advanced possibilities for monitoring air quality, including techniques and devices such as UGAL MDOAS and Sniffer4D v2.

This analysis aims to determine whether emission sources are identified by mobile monitoring. Also, the study aims to compare if the data from both equipment's are suited to identify emissions sources of know pollutants such as: $NO_2$, $SO_2$, $O_3$ and PM. Another direction is to compare the recorded data from both instruments to show how emissions are dispersed on altitudes depending on emission

source such as industry or car traffic (Constantin et al., 2017; Roșu et al., 2017; Roșu et al., 2020).

## MATERIALS AND METHODS

### Study area and measurement system configuration

The study aims to measure air pollution levels and identify emission sources in the city of Galati by using the measurements made on April 18, 2024, along the city's main street. The measurement route is presented in Figure 1 along with general wind speed and direction during measurement, also some with the local air quality stations (AQS). Unfortunately, that day all the were on maintenance routine and no data for comparison with our measurements was possible.

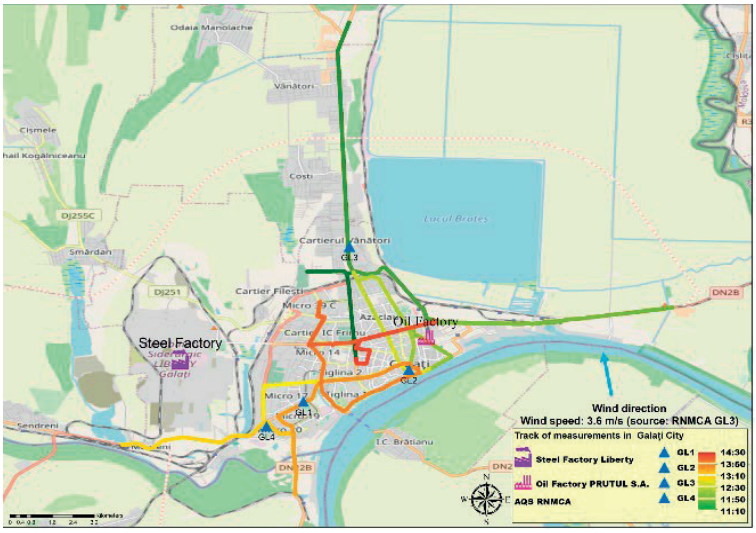


Figure 1. The route on which the measurements were taken correlated with the time interval

This study presents the results of mobile air quality measurements conducted in one of the largest cities in Romania using a remote sensing system developed by the Faculty of Science and Environment, University "Dunărea de Jos" of Galați called UGAL MDOAS, along with a multisensory system, Sniffer 4D. Both instruments were mounted on the same vehicle, allowing simultaneous data collection and facilitating direct comparison between the two systems. (Figure 2).

The UGAL MDOAS system uses differential optical absorption spectroscopy (DOAS) techniques to determine gas densities in the atmosphere with capabilities of measurement of the pollutants located in troposphere as molecules/cm$^2$, while Sniffer 4D uses electrochemical sensors to quantify pollutant concentrations in the air around the car where the system is mounted. These two complementary measurement techniques provide a more comprehensive understanding of air pollution dynamics by combining remote sensing with direct low cost *in situ* monitoring methods.

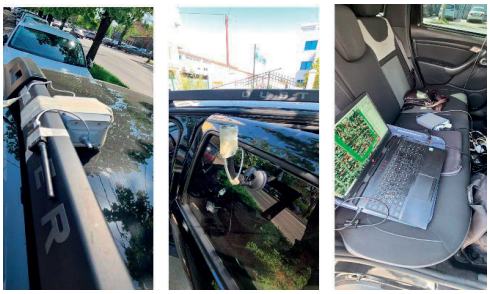

Figure 2. Mobile system setup for Sniffer4Dv2 and MDOAS UGAL

### Equipment and data used

The equipment Sniffer4D V2 is an advanced gas detection and mapping system, designed to simultaneously measure up to 9 types of gases and particles at a time, providing real-time 2D

and 3D maps of their distribution. The system can monitor parameters such as: $PM_{2.5}$, $PM_{10}$, $O_3$, $NO_2$, CO, $SO_2$, VOCs, Odor (OU), $CH_4$, $Cl_2$, $H_2S$, $H_2$, HF, $PH_3$, Gas sampling, wind and speed direction and other customised parameters. Our system configuration has only the sensors for: $PM_{10}$, $PM_{2.5}$, $O_3$ $NO_2$ and $SO_2$. Other features that Sniffer4D V2 has are presented in Table 1.

The system is composed of multi-gas detection hardware and powerful analytical software, that can easily be integrated onto drones or ground vehicles for efficient inspections in various environments. (Godfrey et al., 2022; h*ttps://Enterprise.Dji.Com/Ecosystem/Sniffer-V2*; Jiang et al., 2024; Kulakova et al., 2024; Liu et al., 2024; Prisacariu et al., 2022; Yu et al., 2022).

In addition, by assessing spatial variations in pollutant concentrations, the study analyses the evaluation of stationary monitoring networks in capturing hotspots of transient emission events that would otherwise be overlooked.

Table 1. Specifications and capabilities of Sniffer4D V2 equipment (https://Enterprise.Dji.Com/Ecosystem/Sniffer-V2)

| Category | Specification/Feature |
|---|---|
| Dimensions | 157 × 103 × 87 mm |
| Weight | < 500 g |
| Ingress Protection | IPX2 (protection against vertically dripping water) |
| Explosion Proof | Yes (Ex-proof rated) |
| Casing | Aluminium alloy with anti-EMI shielding |
| Mounting | Internal suspension mechanism for shock and vibration isolation |
| Air Intake | Active air intake system |
| Connectivity | Supports GSM/cellular network connectivity |
| Data Management | - Automatic data backup to SD card (if installed) - Built-in data retrieval algorithm |
| Mobility Potential | Compact and lightweight design suitable for mounting on drones or mobile platforms |

The DOAS technique, in particular the differential oblique column density (DSCD) retrieval method for measuring trace gases in upper atmosphere (troposphere). The system used, called UGAL MDOAS (employs Differential Optical Absorption Spectroscopy), was at "Dunărea de Jos" University of Galați, Faculty of Science and Environment (D. Constantin et al., 2013; D.E. Constantin et al., 2017; Roșu et al., 2017; Roșu et al., 2020). Configuration of the UGAL MDOAS system can be found below in Table 2 for main components and Table 3 for the details on the main component (spectrometer) of the UGAL DOAS instrument.

Table 2. The main components of the UGAL MDOAS

| Component | Description |
|---|---|
| UV–Vis spectrometer | Avantes AvaSpec-ULS2048, one channel Black baffle: internal diameter: 9 mm, length: 2 cm |
| Telescope (baffle+lens) | Black baffle: internal diameter: 9 mm, length: 2 cm Avantes collimating lens; confocal length: 8.7 mm Telescope's field of view: 2.56° |
| Optical fiber | Avantes 600 µm chrome plated brass optical fiber, 1 or 10 m length |
| GPS | Mouse GPS for positioning of recorded data |
| PC | Laptop with win 10 or 11 |

Table 3. The main characteristics of the Avantes UV-Vis spectrometer

| Specification | Description |
|---|---|
| Optical Bench | symmetrical Czerny-Turner, 75 mm focal length |
| Wavelength range | 200-550 nm |
| Resolution | 0.7 nm |
| Sensitivity | 250,000 counts/µW per ms int. time |
| Detector | Back-thinned CCD [1] image sensor 2048 × 16 pixels, non-cooled |
| Signal/Noise | 450:1 |
| Integration time | 1.82 ms–60 s |
| Interface | USB 2.0 high speed, 480 Mbps RS-232, 115,200 bps |
| Data transfer speed | 1.82 ms/scan (USB2.0 [2]) |
| Power supply | Default USB power, or with SPU2 external 12 V DC |
| Dimensions; weight | 175 × 110 × 44 mm (1 channel), 855 g |

## RESULTS AND DISCUSSIONS

Using the data collected by both devices and using a GIS software we have made a series of maps that highlight spatial comparison of the recorded values for each parameter such as: $NO_2$, $SO_2$, $O_3$, $O_4$ and $PM_{2.5}$. The entire measurement timeline for the track analyzed on April 18, 2024, is represented using a color gradient, with measurements taken after 11:00 displayed in green and those after 14:00 shown in red, as illustrated in Figure 1. Spatial analysis of the data using maps enables a detailed evaluation of parameter variations and provides

a clearer understanding of their distribution in the troposphere and their dynamics near the surface.

These observations are essential for identifying and quantifying factors that influence air quality, such as industrial activity within the city, as well as the effects of other variables, including wind direction and the influence of urban topography on the positioning of emission plumes.

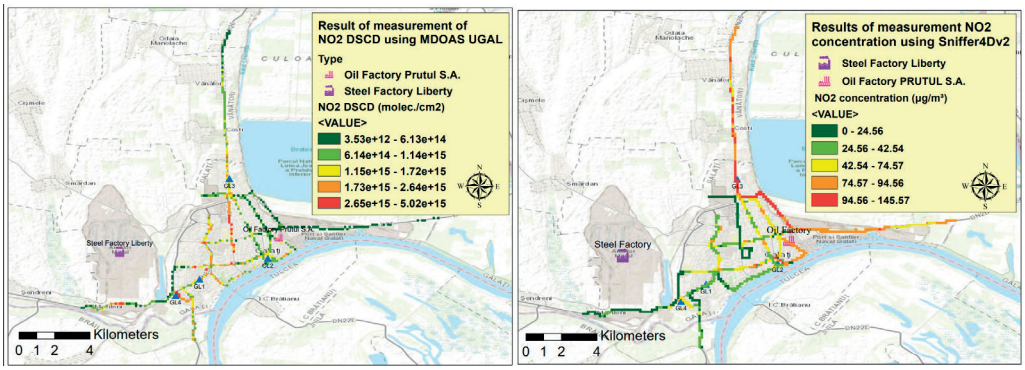


Figure 3. Spatial comparisons of $NO_2$ measured by the mobile system Sniffer 4Dv2 and MDOAS UGAL

As shown in Figure 3, the measurement units differ between the two instruments. This is because the Sniffer4Dv2 detects $NO_2$ concentrations at ground level, reporting values in µg/m³, whereas the MDOAS UGAL (UM) measures the vertical column density of $NO_2$ molecules over a 1 cm² cross-sectional area, expressed in molecules/cm².

Due to these differing units and sensing approaches, comparisons between the two instruments rely on colour-coded ranges. At the beginning of the measurement route, the MDOAS UGAL registers relatively low $NO_2$ values, with the first segments mostly falling into the green to light green range ($3.53 \times 10^{12}$ to $1.14 \times 10^{15}$ molecules/cm²). In contrast, the Sniffer4Dv2 shows moderate to high concentrations for the same segments, predominantly within the orange to red classes (74.57 – 145.57 µg/m³), particularly in the northern and eastern parts of the city.

This discrepancy suggests that, during the measurement period, $NO_2$ was more concentrated near the surface, likely due to localized emissions such as road traffic and industrial activities. The MDOAS UGAL, measuring total column density, might underrepresent surface-level pollution when vertical mixing is limited or when pollutants are trapped in the lower atmospheric layers.

In the southern and central parts of Galați, especially after 12:40 (as inferred from route direction and segment labels), the MDOAS UGAL data reveal greater spatial variability. While most areas, including the zone near the Steel Factory Liberty, show low to moderate $NO_2$ columns (dark green to yellow), a localized hotspot (red) south of the industrial area indicates a significant vertical $NO_2$ presence, possibly from a point source or stack emissions. Meanwhile, the Sniffer4Dv2 continues to show elevated ground-level concentrations in these areas, especially near the oil factory, the steel plant, and key urban intersections, indicating intense surface-level $NO_2$ due to industrial and vehicular emissions. Some segments in the south and near the lake show improved air quality (green), suggesting either fewer emissions or better pollutant dispersion.

These contrasting observations highlight the different sensitivities and spatial resolutions of the instruments. The MDOAS UGAL is influenced by the vertical distribution of $NO_2$, while the Sniffer4Dv2 reflects surface concentrations, where human exposure is most relevant. The data suggest that during the measurement period, $NO_2$ pollution was largely confined to the lower atmosphere, emphasizing the dominant influence of ground-level sources such as traffic and localized industrial activity.

A spatial comparison of $SO_2$ measurements from both devices is presented in Figure 4.

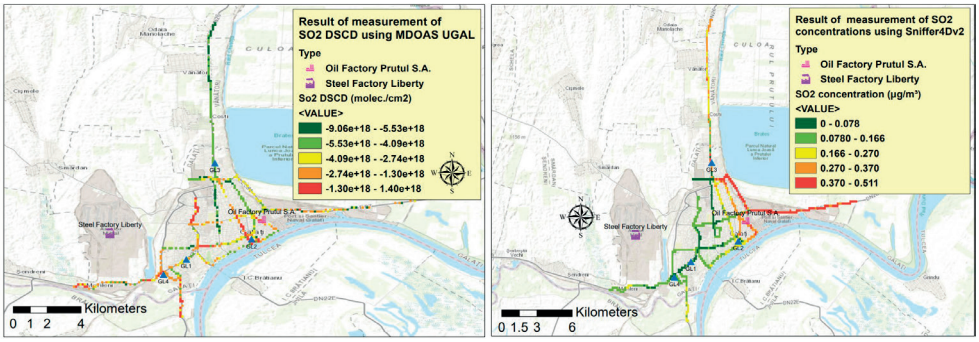


Figure 4. Spatial comparisons of $SO_2$ measured by the mobile sistems Sniffer 4Dv2 and MDOAS UGAL

Figure 4 presents a comparison of $SO_2$ concentrations measured by the MDOAS UGAL system (top) and the Sniffer4Dv2 (bottom). The MDOAS UGAL device measures $SO_2$ vertical column densities, which are especially sensitive to elevated emission sources such as those from industrial chimneys. Accordingly, it detects higher values of $SO_2$ (up to $1.30 \times 10^{18}$ molecules/cm²) around industrial areas, particularly near the Steel Factory Liberty and the Oil Factory Prutul S.A., indicating the influence of high-altitude emissions. In contrast, lower values (as low as $4.86 \times 10^{15}$ molecules/cm²) are observed on the road exiting the city to the north and in less industrialized zones during the first half hour of monitoring, suggesting cleaner atmospheric columns in those areas.

Meanwhile, the Sniffer4Dv2, which measures ground-level $SO_2$ concentrations, records significantly higher values (up to 0.511 µg/m³) in the eastern and north-eastern parts of the city, where emissions are likely trapped near the surface due to low wind speeds or limited vertical mixing. However, in the southwestern industrial area, Sniffer4Dv2 shows lower concentrations (mostly below 0.166 µg/m³), even though MDOAS UGAL reports high column densities in the same area. This contrast supports the conclusion that the industrial $SO_2$ emissions there are released at higher altitudes - above the sensitive range of the Sniffer4Dv2 but well captured by the DOAS system.

It is important to note that the Sniffer4Dv2, being a compact and portable sensor, is primarily designed for ground-level monitoring. However, its capability to be mounted on unmanned aerial vehicles (UAVs) such as drones offers the potential to detect elevated industrial plumes in future studies. This application will be further explored to assess vertical emission structures more comprehensively.

This comparison underscores the complementary nature of the two instruments: while the MDOAS UGAL is effective in detecting elevated plumes from point sources such as stacks, the Sniffer4Dv2 provides detailed information about ground-level exposure relevant for human health assessments, and potentially, in future configurations, about elevated sources as well.

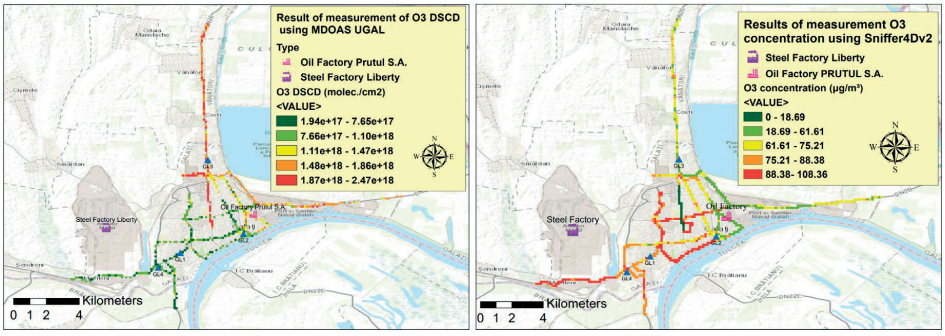


Figure 5. Spatial comparisons of $O_3$ measured by the mobile sistems Sniffer 4Dv2 and MDOAS UGAL

Figure 5 presents the spatial distribution of ozone ($O_3$) concentrations measured by MDOAS UGAL (top panel) and Sniffer4Dv2 (bottom panel). The results show a notable inversion in the spatial trends between the two instruments.

In the northern and eastern sections of the city, before 12:50, the MDOAS UGAL recorded higher ozone column densities, with values predominantly in the range of $1.46 \times 10^{18}$ to $2.04 \times 10^{18}$ molecules/cm², indicating elevated ozone presence in the vertical atmospheric column. In contrast, the Sniffer4Dv2 recorded lower ground-level ozone concentrations in the same areas, generally between 16.01 and 58.31 µg/m³, suggesting better air quality at the surface in those regions. After 12:50, the situation reverses: the MDOAS UGAL measurements show reduced column densities, mostly in the range of $7.66 \times 10^{17}$ to $1.18 \times 10^{18}$ molecules/cm², with only isolated moderate values at traffic intersections. However, the Sniffer4Dv2 records increased ground-level concentrations, with values reaching the highest range of 78.31–103.56 µg/m³, particularly in the central and southwestern parts of the route. These are indicators of poor air quality likely driven by surface-level ozone formation from traffic-related precursors and sunlight-driven photochemical activity.

This comparison emphasizes the different vertical sensitivities of the two instruments. MDOAS UGAL detects total atmospheric column densities, making it sensitive to ozone aloft, while Sniffer4Dv2 provides data directly relevant to human exposure at ground level.

The $O_4$ (oxygen dimer) is formed when two $O_2$ molecules interact and briefly bind together, typically under high-pressure conditions. Although $O_4$ is not stable as a separate pollutant, its absorption features are useful for atmospheric remote sensing, as its concentration is proportional to air density and can provide information about the vertical distribution of pollutants (Wagner et al., 2004). It also plays a role in radiative transfer and can indicate regions with higher aerosol presence (Wagner et al., 2004).

On the other hand, $PM_{2.5}$ is a particulate matter with a diameter less than 2.5 micrometres, which is comparable to O4, is a major air pollutant that may cause serious health risks. Due to their small size, $PM_{2.5}$ particles can penetrate deep into the respiratory system, reaching the alveoli and even entering the bloodstream. Long-term exposure is associated with respiratory and cardiovascular diseases, including asthma, bronchitis, heart attacks, and increased mortality (Pope and Dockery, 2006).

While $O_4$ is measured by the MDOAS UGAL instrument as a tracer of air mass density and potential aerosol interaction in the atmospheric column (Wagner et al., 2004), $PM_{2.5}$ is measured directly at ground level by the Sniffer4Dv2. When interpreted together, these parameters can help infer the vertical and horizontal distribution of particulate pollution: elevated $O_4$ may indicate dense air layers or aerosol-rich zones, which could be linked to high surface $PM_{2.5}$ concentrations under stagnant or stratified atmospheric conditions.

In our study, we also addressed this research direction by leveraging the unique capabilities of the MDOAS UGAL to retrieve $O_4$ column densities and the Sniffer4Dv2 to measure $PM_{2.5}$ concentrations, providing a more comprehensive perspective on atmospheric composition and air quality dynamics, as shown in Figure 6.

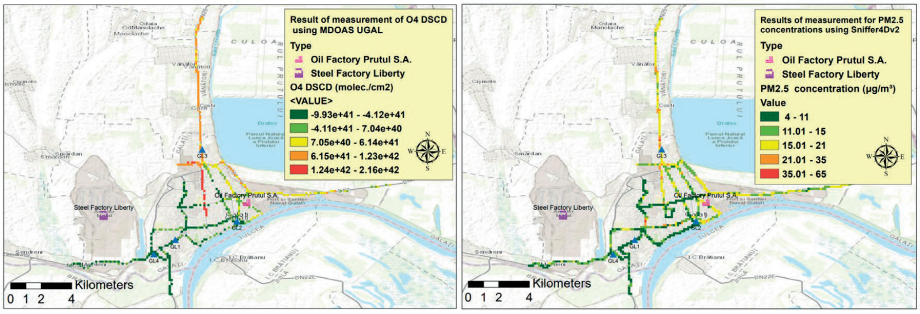


Figure 6. Spatial distribution of $O_4$ and $PM_{2.5}$ measured by MDOAS UGAL respectively Sniffer4Dv2

Figure 6 illustrates the spatial and temporal behaviour of two distinct atmospheric parameters: $O_4$ (oxygen dimer) measured by the MDOAS UGAL system (top panel), and $PM_{2.5}$ (particulate matter < 2.5 μm) measured at ground level by Sniffer4Dv2 (bottom panel).

The upper map shows a clear decreasing trend in $O_4$ differential slant column densities throughout the measurement period. Initially, the $O_4$ values are highest, exceeding $1.62 \times 10^{42}$ molec./cm², but progressively decline, reaching the lowest range ($4.85 \times 10^{41}$ to $1.02 \times 10^{42}$ molec./cm²) toward the end of the route. This pattern is likely influenced by increasing solar radiation and temperature, both of which can affect the stability of $O_4$. The oxygen dimer is transient and weakly bound, and under elevated temperature and strong UV radiation, it can dissociate more rapidly, leading to lower detected column densities as the day progresses. In contrast, the $PM_{2.5}$ ground-level concentrations measured by Sniffer4Dv2 show a more consistent spatial-temporal distribution. Higher values (15-35 μg/m³) are recorded at the beginning of the measurement period, with concentrations gradually decreasing to values below 15 μg/m³, predominantly within the 4-11 μg/m³ range by the second half of the route. This trend reflects the settling or dispersion of fine particulate matter, possibly aided by morning turbulence or changing traffic patterns.

A significant factor contributing to the observed differences between the instruments lies in their measurement geometry and altitude sensitivity. The MDOAS UGAL captures slant column densities through the atmosphere, with sensitivity up to approximately 2 km altitude. Therefore, it can detect pollution plumes situated aloft, which may not be captured by ground-based systems such as Sniffer4Dv2. Conversely, Sniffer4Dv2 records near-surface concentrations, reflecting immediate human exposure but missing elevated layers of pollution.

When Sniffer4Dv2 reports lower values than MDOAS UGAL, it may indicate that the pollution plume is located at higher altitudes - a condition potentially linked to emissions from tall industrial stacks. In particular, areas near factories may exhibit these discrepancies due to elevated release points of $SO_2$ and PM precursors.

Additionally, wind shear and vertical wind profiles can lead to significant variability in pollutant distribution. Wind direction and speed often vary with altitude and time of day. These variations may explain temporal shifts in the measured pollution and the spatial differences between zones with similar sources. For example, plumes emitted during the early morning might drift at higher altitudes due to thermal uplift, while later in the day, ground-level dispersion may dominate. Our future studies will include the research direction where we will incorporate meteorological data such as wind speed, wind direction, and temperature profiles to more accurately characterize the spatial distribution and intensity of emission plumes, as well as to identify their likely sources.

## CONCLUSIONS

This study presented a comparative analysis of trace gases and particulate matter ($PM_{2.5}$) using two complementary mobile measurement systems: the MDOAS UGAL (based on Differential Optical Absorption Spectroscopy) and the Sniffer4Dv2 (a compact air quality system with electrochemical sensors). Despite differences in measurement principles and vertical sensitivity, both instruments consistently identified key pollution hotspots, particularly at major intersections and industrial areas, where emissions from traffic congestion and heavy-duty vehicles were clearly detected.

From the results, $NO_2$, $SO_2$, and $O_3$ measurements showed converging spatial patterns between the two instruments in high-traffic zones, confirming the influence of urban infrastructure and transportation on localized air pollution. The findings presented from the coupling between $O_4$ and $PM_{2.5}$ in which $O_4$ was analyzed from MDOAS UGAL data and $PM_{2.5}$ from Sniffer4Dv2, further highlighted how these systems offer complementary insights. The $O_4$ column densities decreased gradually over time, likely due to increasing solar radiation and atmospheric instability, while $PM_{2.5}$ showed a more stable distribution, initially peaking at 15-35 μg/m³ and declining below 15 μg/m³ toward the end of the route.

Discrepancies observed between the instruments - such as elevated $O_4$ or $NO_2$ column

densities where $PM_{2.5}$ or $NO_2$ ground concentrations remained low - can be explained by their distinct vertical sensitivities. MDOAS UGAL, which integrates slant column densities across atmospheric layers, is sensitive to elevated plumes from point sources such as industrial stacks, whereas the Sniffer4Dv2, positioned at ground level, detects near-surface pollutants more directly linked to human exposure. In cases where MDOAS recorded high values, but Sniffer4Dv2 did not, pollution was likely present at higher altitudes, potentially transported by wind or emitted from tall chimneys. Conversely, elevated surface concentrations with lower column values suggest that pollution remained confined near ground level.

To reduce such discrepancies and enable a more integrated vertical interpretation, future work will focus on converting Differential Slant Column Densities (DSCDs) into true vertical columns using satellite-derived stratospheric corrections (e.g., from OMI or TROPOMI data collected on the same day). Additionally, Air Mass Factor (AMF) simulations using radiative transfer modeling (RTM) will be employed to estimate near-surface pollutant concentrations from DOAS measurements with greater accuracy.

Moreover, integrating high-resolution meteorological parameters such as wind speed, wind direction, temperature, and atmospheric pressure will enhance pollutant transport modeling and source attribution. This multi-parameter framework will provide improved insight into both vertical and horizontal pollution dynamics.

Importantly, this study's dual-system approach has broader implications for urban environmental monitoring and policy development. By combining mobile, high-resolution surface-level data with atmospheric column measurements, the methodology enables a more comprehensive and scalable assessment of air quality. This is particularly valuable in urban areas with complex emission profiles or limited fixed monitoring infrastructure. The approach can support evidence-based urban planning and regulatory strategies, such as optimizing the placement of air quality stations, identifying priority areas for emission reduction, and informing traffic and industrial zoning decisions.

In summary, the integration of complementary remote sensing and low-cost sensor technologies offers a robust and flexible monitoring framework. It strengthens both scientific understanding and policy-making capacity, paving the way for more adaptive and informed air quality management in rapidly urbanizing environments.

## ACKNOWLEDGEMENTS

The authors acknowledge the support of the project "Support for the operation of Romania's facilities within the ACTRIS ERIC research infrastructure", MySMIS code 309113, funding contract No. 309010/19.12.2024. The autors acknowledge that equipement used for this study are part of REXDAN Research Infrastructure (REXDAN RI) and European Center of Environmental Excellence (ECEE) from Faculty of Science and Environment, "Dunărea de Jos" University of Galați.

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