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ASSESSING ACCURACY OF LOW-COST COMPACT SYSTEM VERSUS STANDARD AIR QUALITY SYSTEMS

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Abstract

Air pollution has emerged as a pressing concern in large urban areas, often stemming from sources like intensified traffic and industrial activities within city limits. Addressing this issue requires an understanding of air quality levels, leading to the adoption of low-cost, portable air quality monitoring systems. In our research, we conducted tests using a compact mobile air quality system, SNIFFER 4D (SN), comparing its performance against conventional air quality monitors utilizing standardized methods such as chemiluminescence and spectrometry. The equipment was stationed at the REXDAN research facility situated along one of Galati city's main roads. The primary objective of our study was to evaluate the reliability and suitability of the SN for detailed analysis of trace gases like NO_2*,* O_3*, and* PM_{10}*, by cross-referencing data with readings from standard instruments capable of measuring individual trace gases. Data collection spanned from August 17 to August 30, 2023. Our findings indicate that the SN system proved to be a stable and sophisticated tool for conducting high-resolution studies on local and regional air pollution, encompassing pollutants such as* NO_2*,* O_3*, and* PM_{10}*.*

***Key words**: Low-cost air quality monitoring systems, air pollution, air quality station, standard air quality system, trace gases,* PM_{10}*.*

INTRODUCTION

Air pollution caused by human activities, such as industry, agriculture, transportation, and other polluting sectors is a worldwide environmental problem. Many studies are performed to illustrate the past, actual level of emissions using in-situ measurements (Hofman et al., 2022; Iannarelli et al., 2022; Leifer et al., 2022; Li K. et al., 2022; Specht et al., 2022; Sturm et al., 2022; Zhao C. et al., 2022), ground-based remote sensing measurements (Constantin et al., 2013; Merlaud et al., 2018; Rosu et al., 2019b; Roșu et al., 2018; 2019a; 2021), satellite instruments (Gupta et al., 2006; Hoff & Christopher, 2009; Leifer et al., 2022; Ung et al., 2021; Zhang et al., 2020; Zhao C. et al., 2022). In general, air pollutants include both gaseous (NO_2, O_3, etc.) and particulate matter (PM) caused by burning of fossil fuels during different activities (industrial, traffic, warming, etc.) that occur largely in large human agglomerations such as large cities.

Urban air quality has emerged as a critical concern, impacting public health, environmental sustainability, and overall quality of life (Fenger, 1999; Gulia et al., 2015; Hopke et al., 2008; Mocanu et al., 2023). Following, the necessity for the utilization of low-cost air quality systems in urban areas has become increasingly evident. Low-cost air quality systems offer several advantages in urban areas, including affordability, scalability, real-time data availability, and enhanced community engagement. Additionally, their scalability enables the creation of comprehensive monitoring networks across urban landscapes, capturing spatial variations in pollution levels (Kelechi et al., 2022; Li J. et al., 2020; Morawska et al., 2018; Penza et al., 2017). Real-time data provided by these systems enables timely responses to pollution events, facilitating targeted interventions to improve air quality. However, challenges such as lower accuracy and precision, the need for frequent calibration and maintenance, limited sensor capabilities, and concerns about data quality assurance remain significant disadvantages of low-cost air quality systems (Clements et al., 2017; Idrees & Zheng, 2020; Ikram et al., 2012; Karagulian et al., 2019). Calibrating low-cost sensors is essential to ensure the accuracy and reliability of air quality data collected over time series measurements. Proper calibration involves adjusting sensor readings to match known reference values, minimizing the risk of measurement errors, and ensuring consistency in data interpretation (González Rivero et al., 2023; Han et al., 2021; Ionascu et al., 2021).

In this study, we present the results of a direct comparison of measurements for NO_2 (nitrogen dioxide), O_3 (ozone), and PM_{10} (suspended particulate matter) using a compact low-cost air quality system with the measurement of the same trace gases using standard air quality equipment deployed near or at the same location for two weeks. The study aims to evaluate the factory accuracy (errors, correlation factors, etc.) of the low-cost system with respect to standard equipment.

MATERIALS AND METHODS

Study area and localization

The testing of the compact air quality system Sniffer 4Dv2 (SN) data for NO_2, O_3, and PM_{10} against other standard one-to-multiple trace gas monitors took place at the Rexdan Research Infrastructure (REXDAN), situated on a major thoroughfare in Galati, a city in the SE of Romania (45°26′22″N 28°2′4″E) (98 George Coşbuc Street, Galati, Romania).

This location was selected due to its accessibility for powering the instruments and its proximity to one of the busiest traffic-congested roads in Galati, with high levels of pollution (Roşu et al., 2018; Rosu et al., 2023). Also, the location of the experiment is close to one of the local air quality stations (AQS) GL-2, which is part of a national network for air quality monitoring (Rețeaua Națională de Monitorizare a Calității Aerului - RNMCA), from which data were collected, to be used for comparison of SN data The map that presents the spatial location of the deployment of equipment along with the position of AQS GL2 is presented in the Figure 1.

Figure 1. Location of the deployment of the measuring equipment REXDAN RI and the location of the AQS GL2 from RNMCA

We chose to utilize data from GL2 AQS because of the specification about the spatial limit of detection of 5 kilometers around it, thus covering our measurement site, declared by RNMCA and presented in a previous study where we used the SN system to quantify spatial extend of pollution in Galati city (*Calitate Aer | Acasă*, n.d.; Rosu et al., 2023).

The period of measurements is from 17 August to 30 August 2023 when all equipment was deployed for synchronous measurement at REXDAN RI inside a climatized box, located in the courtyard as it is presented in the figure from below. The climatized box can maintain a constant temperature while the external air is brought by a pump system with a flow of 5 L/min. We chose this climatized box to remove data drifts of air pollutants caused by temperature variability, especially for electrochemical sensors and other spectroscopic effects that can generate errors in air pollutants measurements.

Figure 2. The temperature-controlled box where all air quality requirements were deployed for consistency of data (removing temperature-driven drifts from data series)

Equipment and data

For our study, we used data collected during 17-30 August 2023 from GL2 RNMCA AQS, and data recorded by each of the following standard equipment: Model 405 nm $NO_2/NO/NO_x$ Monitor (2B NO_2); Sniffer 4Dv2 (SN- the low-cost air-quality system: NO_2, O_3, PM_{10}); Personal Ozone Monitor (POM - 2B O_3). Each of the standard air quality measurement equipment and AQS are presented in detail below.

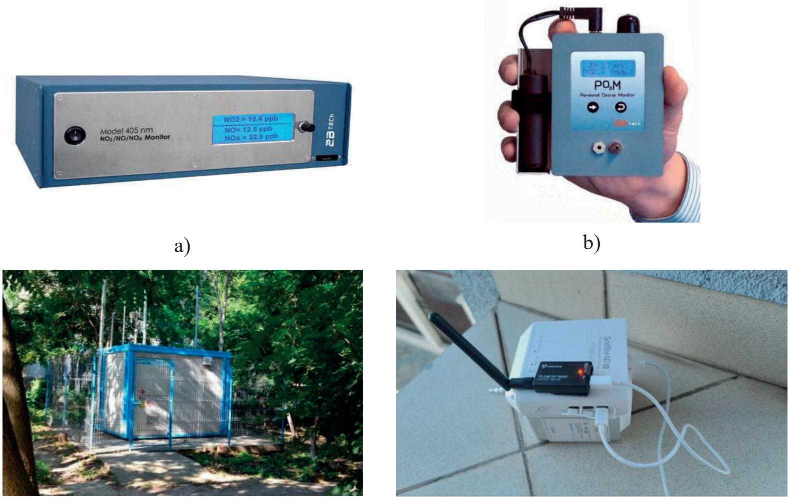
The local air quality monitoring network in Galati City is managed by the local administrative office of the Environmental Protection Agency of Galati (Agenția de Protecția Mediului din Galați - APM GL). Comprising four stationary Air Quality Stations (AQS) situated across various areas of the city, each AQS is equipped with monitors and sensors housed within a temperature-controlled container to continuously measure specific pollutants. The parameters measured by each AQS in Galati City encompass a comprehensive array of air pollutants and meteorological data. Of particular interest for our study are the following pollutants, along with their respective determination methods: particulate matter (PM_{10} - Light Scattering Particle), nitrogen dioxide (NO_2 - chemiluminescence), and ozone (O_3 - ultraviolet photometric analyzer). More information about the equipment that is used at each AQS is presented in Table 1. The data of each AQS can be downloaded from the database available at (*Calitate Aer | Acasă*, n.d.). For our study, we downloaded the data from GL2 RNMCA for the period of the in-situ campaign.

The Personal Ozone Monitor (POM) by 2B Technologies is a lightweight and portable scientific equipment designed for personal exposure monitoring of ozone (O_3) levels. Featuring advanced sensor technology, the POM delivers accurate and real-time measurements of ozone concentrations in ambient air. Its compact design and wearable form factor make it an ideal measurement of ozone exposure, providing valuable insights into air quality and potential health risks associated with ozone exposure. The POM was used in various studies including ship emissions measurements and other studies that present the monitoring of ozone production and emissions sources (In't Veld et al., 2021; Stanier et al., 2021; *What Happens to Ozone Inside a Ship Plume? | 2B Tech*, n.d.). The data of POM (2B O_3) is stored internally and can be downloaded via a USB cable.

The Model 405 nm $NO_2/NO/NO_x$ Monitor by 2B Technologies is a compact and versatile device designed to accurately measure nitrogen dioxide (NO_2), nitric oxide (NO), and nitrogen oxides (NO_x) concentrations. Utilizing advanced 405 nm LED absorption technology, it provides precise and real-time measurements of these key pollutants in various environmental settings. Its portable design and user-friendly interface make it suitable for both stationary and mobile monitoring applications, enabling efficient and reliable air quality assessments (Dam et al., 2022; Li J. et al., 2021; Rangel et al., 2022). The data of Model 405 nm NO_2/NO/NO_x Monitor (2B NO_2) is stored internally or on an SD card and can be downloaded via a USB cable or by reading the SD card.

The Sniffer 4Dv2 air quality system is a highly portable and compact device, weighing less than 350 grams. This makes the SN system an ideal equipment for mobile (aerial - drone; and car-based measurements) and *in situ* measurements of various pollutants emissions (Rosu et al., 2023). It employs multiple sensors utilizing various determination methods to measure up to nine air quality parameters, including temperature and humidity. Utilizing a pump mechanism, the system draws external air through a frontal inlet to the sensors housed within its main body. Sensors can be configured in different combinations to perform quantitative emissions studies of various air pollutants made by man-made sources such as industry, traffic, or natural sources, in accord with the desired outcome, such as personal exposure monitoring, urban air quality monitoring, or industrial emissions monitoring (Godfrey et al., 2022; Hay et al., 2023; Kim et al., 2021; Miao et al., 2022, 2024; Rosu et al., 2023; Senarathna et al., 2022). The setup of SN used in our study includes sensors for the measurement of the following air pollutants: NO_2, O_3, and PM_{10}. The data is transmitted in real-time using radiotelemetry (maximum range 1-5 km) that came along with the SN system. An image of the SN system during the test for real-time data transmissions via radio telemetry from outside to the PC located inside the building is presented in the below figure. Representative images of the other deployed equipment and AQS GL2 are presented in Figure 3.

The specifications of each equipment used during the in-situ measurement campaign at REXDAN RI from 17 - 30.08.2023, data availability, type of measured pollutant, method of measurement, the range of detection, and detection limit of each equipment according to manufacturer specifications are presented in Table 1.



a) b)

c) d)

Figure 3. Air quality station and equipment used to measure NO_2, O_3 and PM_{10} from 17-30.08.2023 at RI REXDAN (including AQS GL2): a) Model 405 nm NO_2/NO/NO_x Monitor - 2B Tech (G. Zhao et al., 2022); b) POM™, Personal Ozone Monitor™ - 2B Tech (He et al., 2022a); c) Local air quality station (RNMCA GL2) (Calitate Aer | Acasă, n.d.); d) Air quality system Sniffer 4Dv2 - Soarability (during the test of data transfer to PC using radio telemetry)

Table 1. Specification of equipment and GL2 AQS during in-situ campaign at REXDAN RI from 17-30.08.2023 (42iQ NO-NO_2-NO_x Analyzer, n.d.; 49iQ Ozone Analyzer, n.d.; 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe. Vol. 152 - Google Search, n.d.; Model 5028i Continuous Particulate Monitor, n.d.; He et al., 2022; Li J. et al., 2021)

Instrument/ Equipment	Producer	Pollutant measured	Method of measurement	Range of measurement	Detection limit	Data availability during the experiment
RNMCA GL2	Thermo Fisher Scientific	O_3	Spectroscopy ultraviolet photometric	0 - 200 ppm	0.5 ppb	Available
	Thermo Fisher Scientific	NO_2	Spectroscopy chemiluminescence	0 - 20 ppm	0.4 ppb	Not available
	Thermo Fisher Scientific	PM_{10}	Light Scattering Particle	0 - 10000 µg/m^3	0.1 µg/m^3	Available
POM (Personal Ozone Monitor)	2B Tech	O_3	UV Absorption at 254 nm	0 - 10 ppm	0.1 ppb	Available
Model 405 nm NO2/NO/NOx Monito	2B Tech	NO_2	Direct absorbance of NO2 at 405 nm	0 - 10 ppm	0.1 ppb	Available
Sniffer 4Dv2	Soarability Technology	NO_2+O_3	Electrochemical	0 - 11 ppm	5 ppb	Available
	Soarability Technology	O_3	Electrochemical	0 - 11 ppm	5 ppb	Available
	Soarability Technology	PM_{10}	Laser scattering/Light scattering	0 - 1000 µg/m^3	1 µg/m^3	Available
	Soarability Technology	NO_2	Electrochemical	0 - 11 ppm	5 ppb	Available

The number of sampled data, time resolution of sampling of each equipment used, and time resolution used for comparison of data recorded during 17-30 August 2023 are presented in Table 2. For comparison, data for all equipment was averaged to an hourly mean. The statistical Pearson correlation factor was produced using the raw data of all equipment and AQS.

Table 2. Sample specifications for each of the equipment used during the in-situ measurement campaign period 17-30 August 2023 at REXDAN RI

Instrument/ AQS	SN	AQS GL2	2B NO_2 Monitor	2B O_3 Monitor
Sampling specifications				
Number of Samples	19027	312	9740	9740
The time resolution of sampling	1 s	hourly	5 s	5 s
Average time resolution used for comparison	1 hour	1 hour	1 hour	1 hour

RESULTS AND DISCUSSIONS

Diurnal variations of NO_2, O_3 and PM_{10}

In the first part of our study, we analyzed the data gathered with the SN system, 2B monitors (NO_2 and O_3), and AQS data for the period 17-30 August 2023. The diurnal variation of hourly means, for the entire period of measurements, was compared to the other equipment for the following air pollutants: NO_2, O_3, and PM_{10} (Figure 4).

Figure 4 shows that the NO_2 recorded by SN has similar values as the 2B equipment, a maximum value of 71 µg/m^3 at 1 AM close to the maximum value of 63 µg/m^3 recorded at midnight by the 2B NO_2 monitor with. The high values recorded at the end of each day and past midnight are caused by the compression of the planetary boundary layer (PBL) that captures and concentrates the air pollutants mostly above urban areas where emission sources are more present (Badarinath et al., 2009; Bravo-Aranda et al., 2017; Falasca et al., 2021; Wyngaard, 1988).

Analyzing the general trends of diurnal variation, we observe that both SN and 2B equipment show a descending trend from midnight to 7 AM, when high values are again shown by both equipment's, which are caused mostly by traffic agglomeration during mornings. A decrease in concentrations during morning is observed, probably due to the decompression of PBL and thus a greater dilution of pollution level (Badarinath et al., 2009). Also, another cause can be the fact that NO_2 converts into NO and O_3 by the action of UV and visible solar radiation (Clapp & Jenkin, 2001; Han et al., 2011; Mazzeo et al., 2005). During the afternoon and evenings, both equipment recorded high values, mostly as a cause of decrease in the intensity of solar radiation, thus NO_2 is no longer photochemically converted to O_3 and NO. Also, this is the time when traffic increases due to the end of the working hours (rush hours). Moreover, the PBL is dropping as a cause of temperature decrease due to lack of sunlight (IR radiation).

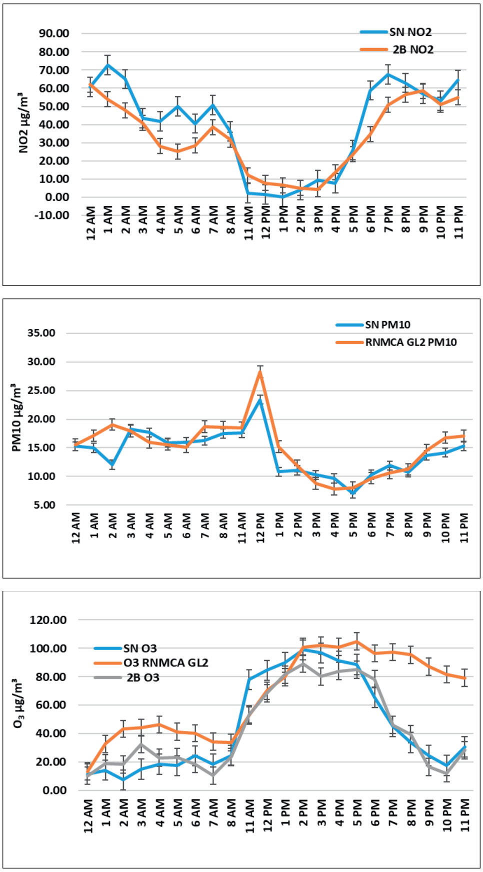


Figure 4. Diurnal variation of NO_2 (top figure), PM_{10} (middle figure), and O_3 (down figure) recorded by SN versus the other standard equipment (2B NO_2, 2 B O_3, AQS GL RNMCA)

A Pearson correlation factor between the two data sets of R = 0.92 was found. This shows that SN is a reliable equipment for monitoring local/regional NO_2 emissions (Rosu et al., 2023). Differences between the recorded diurnal values of SN NO_2 diurnal data versus the 2B NO_2 data are presented in Table 3. The SN air quality system records higher values at maximum NO_2 pollution level, with a mean value of 10.04 $\mu g/m^3$, and underestimates the NO_2 values when the NO_2 pollution is low with a mean value difference between SN data and 2B NO_2 of -2.46 $\mu g/m^3$. The mean value of the differences between NO_2 data recorded by SN and 2B NO_2 is 6.35 $\mu g/m^3$ which is 10 times lower than the maximum values recorded by both equipment's. Therefore, the SN air quality system is suitable and precise equipment for regional and local monitoring of NO_2 pollution level.

The PM_{10} data (Figure 4) measured with SN and RNMCA GL2, have similar variations. High values are recorded at 12 PM, with 28.3 $\mu g/m^3$ for RNMCA GL and 23.43 $\mu g/m^3$for SN air quality system. Differences between the two data sets are observed when the PM_{10} pollution is high, with an average difference between 7.01 $\mu g/m^3$, and 1.89 $\mu g/m^3$. The small differences between SN and RNMCA GL2 show that our low-cost air quality sensor is a sensitive instrument for PM_{10} measurements for local to regional areas if we take into account that RNMCA GL2 is an urban background station that has a sampling area of 5 km (*Calitate Aer | Stații*, n.d.).The general diurnal variation is similar for both air quality systems, with an increase from 12 AM to 1 PM, and a decrease during the afternoon, Higher values are recorded by both instruments at noon, possibly due to traffic and to road infrastructure works which intensified in the past months near the study area.

The daily variation for O_3 presented in Figure 4 shows similar trends between SN, 2B O_3, and RNMCA GL2, with high values above 60 $\mu g/m^3$ of O_3 being recorded by all equipment between 10 AM and 6 PM, due to the photochemical conversion of NO_2 (decrease of NO_2 can be observed in the same period in top graph in Figure 3) plume into O_3 when sun radiance increases during the day. This is backed up by the peak of high O_3 concentration values that can be observed in the data measured by all equipment around 1-2 PM when sun activity reaches its peak and thus more radiation for photo dissociation of NO_2 into O_3 is present. The O_3 measured by RNMCA GL2, is much higher after 4 PM, compared to SN and 2B O3 data. This may be since emissions in the area around RNMCA GL2 are higher than at the location of our instruments.

The Pearson correlation coefficient for diurnal variations recorded by SN with data recorded by the other standard equipment (2B O_3, 2B NO_2, RNMCA GL2) along with standard deviation (SD), and differences for average, maximum, and minimum are presented in Table 3.

For NO_2 measurements there is a correlation between SN and 2B NO_2 data of $R^2 = 0.97$, which shows that SN is highly sensitive to small variations, like standard NO_2 monitors (2B NO_2).

Table 3. Standard deviation and correlations of SN data with the data from standard equipment, differences between SN and standard equipment for diurnal data

	SN NO_2	**2B NO_2**	**SN O_3**	**2B O_3**	**O_3 RNMCA GL2**	**SN PM_{10}**	**RNMCA GL2 PM_{10}**
R^2 correlation for SN	1.00	**0.97**	1.00	**0.95**	**0.83**	1.00	**0.88**
SD (µg/m³)	5.31	4.17	7.14	6.15	6.20	0.80	1.00
Minimum difference SN - standard equipement	0.00	-10.04	0.00	-7.29	-7.55	0.00	-7.01
Average difference SN - standard equipement	0.00	6.35	0.00	2.50	-2.35	0.00	-1.00
Maximum difference SN - standard equipement	0.00	2.46	0.00	2.48	1.75	0.00	1.89

Daily average results

The daily average variation for NO_2, PM_{10}, and O_3 measured by the SN air quality system versus the standard air quality monitors (including RNMCA GL2) are presented in Figure 5.

The NO_2 concentration measured by both SN and 2B-NO_2 have similar daily variation, with a minimum during the first weekend and increased values during the second week, regardless of the day. This may be related to:

1) an increased traffic intensity caused by people coming back from vacation since it is the last week of August;
2) different meteorological conditions that affect NO_2 concentration (Voiculescu et al., 2020).

Small differences between data from the two equipment are observed, with a mean of 0.16 µg/m³. The differences between the two instrument readings are presented in Table 4 along with the standard deviation of the data sets. Also, the correlation analysis of the two data sets shows a very good agreement with a Pearson correlation coefficient of $R^2 = 0.98$.

The PM_{10} daily average observed by both SN and RNMCA GL2 has maximum values on August 28-th and 17-18 August (in the middle of the week). The differences between the two data sets during low PM_{10} pollution are -3.51 µg/m³. This shows that the SN system records lower values when the pollution is low, which may suggest that there is a threshold for at low PM_{10}.

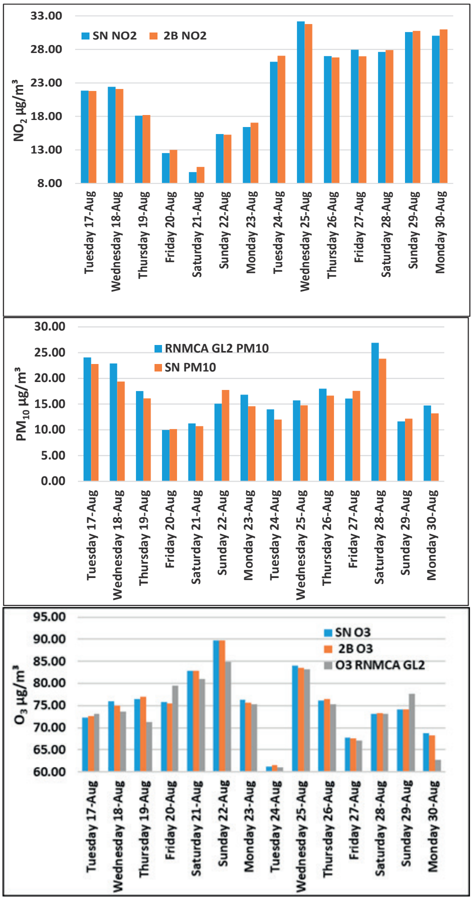


Figure 5. 4 Daily average concentration of NO_2 (top figure), PM_{10} (middle figure), and O_3 (down figure) recorded by SN versus the other standard equipment (2B NO_2, 2 B O_3, AQS GL RNMCA)

Opposingly, during high PM levels, differences are positive (2.6 μg/m^3), suggesting that the SN system is overestimating the PM_{10} concentration at high levels of pollution.

The average difference between the two data sets is about -0.92 μg/m^3 which indicates that SN is recording a lower value of PM_{10} than RNMCA GL2. This may be due mainly to the fact that the two pieces of equipment are not collocated.

The O_3 daily average recorded by SN, RNMCA GL2, and 2B O_3 are shown in Figure 5. All three datasets show similar behaviour, with the highest value on August 22-nd and 25-th. The differences between daily average concentrations of O_3 recorded by SN and RNMCA GL2 are about 5.62 μg/m^3 at high pollution levels and about -4.08 μg/m^3 at low pollution levels. The mean difference between SN O_3 data and RNMCA GL2 is about 1.01 μg/m^3, which means that the SN system measured higher values of O_3 than RNMCA GL2. The correlation factor between SN and RNMCA GL2 for O_3 daily concentration average is R^2 = 0.87. Interestingly, a clear absolute minimum during the 2 weeks appears on August 24-th (Tuesday) and shows up for all three equipment.

Small differences between the two data sets are measured at a high level of pollution with a value of 0.94 μg/m^3 O_3 and with -0.38 μg/m^3 at a low level of pollution level. These findings support the idea that SN equipment is a very good instrument for the determination of daily average concentration levels with a mean difference of -0.93 μg/m^3 with respect to the values recorded by standard equipment (2B O_3). The correlation for all trace gases recorded by SN along with data recorded by the other standard equipment (2B O_3, 2B NO_2, RNMCA GL2) along with standard deviation (SD), and differences for average, maximum and minimum are presented in Table 4.

Table 4. Standard deviation and correlations of SN data with the data from standard equipment, differences between SN and standard equipment for daily averaged data

	SN NO_2	**2B NO_2**	**SN O_3**	**2B O_3**	**RNMCA GL2 O_3**	**SN PM_{10}**	**RNMCA GL2 PM_{10}**
R2 correlation for SN	1.00	0.98	1.00	0.99	0.87	1.00	0.86
SD (μg/m³)	1.93	1.89	1.90	1.89	1.90	1.12	1.31
Minimum difference SN - standard equipement	0.00	-0.94	0.00	-0.38	-4.08	0.00	-3.51
Average difference SN - standard equipement	0.00	-0.16	0.00	0.10	1.02	0.00	-0.93
Maximum difference SN - standard equipement	0.00	0.96	0.00	0.96	5.63	0.00	2.67

CONCLUSIONS

We have shown that the SN system accurately measures atmospheric pollutants concentration when used for mobile measurements (Godfrey et al., 2022; Li J. et al., 2021; Rosu et al., 2023; Stanier et al., 2021). High correlation coefficients exist between data measured by standard types of equipment, including AQS, when referring to diurnal variation and daily average values. The SN equipment seemingly underestimates concentrations during low pollution events for NO_2, PM_{10}, and O_3.

In order to find out with what value the SN is underestimate the value of air pollutants, long term in-situ data is required to accurately find the exact value which will be done in future studies. Also, the SN system can be calibrated, as the manufacturer lets us manipulate the offsets of sensor data, with these data sets to perform more precise measurements of air pollutants with respect.

These results show that SN equipment is suited for long-term air pollution studies both in-situ and mobile measurements (Rosu et al., 2023) to identify and evaluate the diurnal variation concentration of such air pollutants (NO_2, O_3, and PM_{10}) and identification of air pollution emissions sources.

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