



LOW-COST SENSOR NETWORKS: INTEGRATING DRONE AND STATIONARY STATIONS FOR AIR QUALITY MONITORING

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ABSTRACT

Objective: This study addresses the issue of using low-cost sensors to survey greenhouse gas emissions. Two sets of sensors were used in this study: one designed to be mounted on a drone and the other intended for stationary measurements. The optimization of an algorithm in the operation of the sensors, presented here, was used to reduce energy consumption; every seven seconds, a scan is performed on all the sensors in the set.

Theoretical Framework: The work presents an integrated system for monitoring emissions and tracking stability through statistical analyses, including the use of the Allan Variance method to analyze time-series data. This method is especially effective for assessing the noise and stability of measurements. Data acquisition from Arduino platforms offers a variety of hardware options, providing energy efficiency for logging applications.

Method: The methodology outlined in this report enables the unified operation of multiple sensors, presenting a low-cost data logging platform designed for long-term use in remote or harsh environments. In this initial test, three breakout boards from the open-source Arduino ecosystem are integrated into the core of the data logger. The project also introduces drone technologies that expand the coverage area and extend the operational lifespan of the modular design.

Results and Discussion: This article explores the feasibility of using low-cost sensors as an alternative method for monitoring greenhouse gases and particulate matter in situations where deploying reference-grade instruments are not practical. Stability tests were carried out by measuring the same air sample under consistent atmospheric conditions with both sensor sets over a period of several hours. Long-term testing of the low-cost sensor system took place in an open field, with experiments spanning 26 hours. The Allan deviation plot, derived from these measurements for both sensor sets, is presented. The results indicate that the CO₂ precision of the system is better than 20 ppm.

Research Implications: The sensor system presented offers an innovative, low-cost, and portable solution for detecting greenhouse gas emissions. Importantly, the system has proven to be reliable, effectively capturing fluctuations and associated uncertainties as demonstrated through statistical analyses. Widespread deployment of such measurement stations could enable the creation of a comprehensive monitoring network, providing the coverage and responsiveness needed to address climate risks like those we currently face.

Originality/Value of the Research: This study presents the development of a low-cost sensor system designed for practical and efficient environmental monitoring. The system is adaptable for deployment over large areas, whether through a network of fixed stations or mobile drone platforms. Data acquired during the measurements are systematically stored and analyzed using Allan variance statistics, processed with OriginPro software, ensuring a robust assessment of sensor stability and precision.

Keywords: GHG and particulate matter monitoring, Low-Cost sensor network detection, Environmental Monitoring, Allan variance, UAV's.

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REDES DE SENSORES DE BAIXO CUSTO: INTEGRAÇÃO DE DRONES E ESTAÇÕES ESTACIONÁRIAS PARA A MONITORIZAÇÃO DA QUALIDADE DO AR

RESUMO

Objetivo: Este estudo aborda o uso de sensores de baixo custo para o monitoramento de emissões de gases de efeito estufa. Foram utilizados dois conjuntos de sensores: um projetado para ser montado em drones e outro destinado a medições estacionárias. A otimização de um algoritmo para o funcionamento dos sensores, apresentada neste trabalho, foi utilizada para reduzir o consumo de energia; a cada sete segundos, é realizada uma varredura em todos os sensores do conjunto.

Referencial Teórico: O trabalho apresenta um sistema integrado para o monitoramento de emissões e o acompanhamento da estabilidade por meio de análises estatísticas, incluindo o uso do método de Variância de Allan para análise de séries temporais. Esse método é especialmente eficaz para avaliar o ruído e a estabilidade das medições. A aquisição de dados a partir de plataformas Arduino oferece uma variedade de opções de hardware, proporcionando eficiência energética para aplicações de registro de dados.

Método: A metodologia descrita neste relatório permite a operação unificada de múltiplos sensores, apresentando uma plataforma de registro de dados de baixo custo, projetada para uso prolongado em ambientes remotos ou de difícil acesso. Neste teste inicial, três placas de circuito (breakout boards) do ecossistema open-source Arduino foram integradas ao núcleo do registrador de dados. O projeto também introduz tecnologias de drones que ampliam a área de cobertura e aumentam a vida útil operacional do design modular.

Resultados e Discussão: Este artigo investiga a viabilidade do uso de sensores de baixo custo como método alternativo para o monitoramento de gases de efeito estufa e material particulado em contextos onde o uso de instrumentos de referência não é viável. Testes de estabilidade foram realizados medindo a mesma amostra de ar sob condições atmosféricas constantes com ambos os conjuntos de sensores, durante várias horas. O teste de longo prazo do sistema de sensores de baixo custo foi conduzido em campo aberto, com experimentos que totalizaram 26 horas. O gráfico da variância de Allan, obtido a partir dessas medições com ambos os conjuntos, é apresentado. Os resultados indicam que a precisão na medição de CO₂ é superior a 20 ppm.

Implicações da Pesquisa: O sistema de sensores apresentado oferece uma solução inovadora, portátil e de baixo custo para a detecção de emissões de gases de efeito estufa. É importante destacar que o sistema demonstrou ser confiável, capturando com eficácia as flutuações e incertezas associadas, conforme demonstrado pelas análises estatísticas. A ampla implementação de estações de medição como as propostas pode possibilitar a criação de uma rede de monitoramento abrangente, proporcionando a cobertura e a capacidade de resposta necessária para lidar com riscos climáticos como os que enfrentamos atualmente.

Originalidade/Valor da Pesquisa: Este estudo apresenta o desenvolvimento de um sistema de sensores de baixo custo projetado para um monitoramento ambiental prático e eficiente. O sistema é adaptável para uso em grandes áreas, seja por meio de uma rede de estações fixas ou por plataformas móveis com drones. Os dados adquiridos durante as medições são sistematicamente armazenados e analisados utilizando estatísticas de “Allan Variance”, processadas com o *software* OriginPro, garantindo uma avaliação robusta da estabilidade e precisão dos sensores.

Palavras-chave: Monitoramento de GEE e material particulado, Rede de detecção com sensores de baixo custo, Monitoramento Ambiental, Variância de Allan, UAV's.

REDES DE SENSORES DE BAJO COSTE: INTEGRACIÓN DE DRONES Y ESTACIONES ESTACIONARIAS PARA LA MONITORIZACIÓN DE LA CALIDAD DEL AIRE

RESUMEN

Objetivo: Este estudio aborda el uso de sensores de bajo coste para la monitorización de emisiones de gases de efecto invernadero. Se utilizaron dos conjuntos de sensores: uno diseñado para ser montado en drones y otro destinado a mediciones estacionarias. La optimización de un algoritmo para el funcionamiento de los sensores, presentada en este trabajo, se empleó para reducir el consumo de energía; cada siete segundos se realiza un escaneo en todos los sensores del conjunto.

Marco Teórico: El trabajo presenta un sistema integrado para la monitorización de emisiones y el seguimiento de la estabilidad mediante análisis estadísticos, incluyendo el uso del método de Varianza de Allan para el análisis de



series temporales. Este método es especialmente eficaz para evaluar el ruido y la estabilidad de las mediciones. La adquisición de datos a partir de plataformas Arduino ofrece una variedad de opciones de hardware, proporcionando eficiencia energética para aplicaciones de registro de datos.

Método: La metodología descrita en este informe permite la operación unificada de múltiples sensores, presentando una plataforma de registro de datos de bajo coste, diseñada para uso prolongado en entornos remotos o de difícil acceso. En esta prueba inicial, se integraron tres placas de circuito (breakout boards) del ecosistema open-source Arduino al núcleo del registrador de datos. El proyecto también introduce tecnologías de drones que amplían el área de cobertura y aumentan la vida útil operativa del diseño modular.

Resultados y Discusión: Este artículo investiga la viabilidad del uso de sensores de bajo coste como método alternativo para la monitorización de gases de efecto invernadero y material particulado en contextos donde no es viable el uso de instrumentos de referencia. Se realizaron pruebas de estabilidad midiendo la misma muestra de aire bajo condiciones atmosféricas constantes con ambos conjuntos de sensores, durante varias horas. La prueba a largo plazo del sistema de sensores de bajo coste se llevó a cabo en campo abierto, con experimentos que totalizaron 26 horas. Se presenta el gráfico de la varianza de Allan obtenido a partir de estas mediciones con ambos conjuntos. Los resultados indican que la precisión en la medición de CO₂ es superior a 20 ppm.

Implicaciones de la Investigación: El sistema de sensores presentado ofrece una solución innovadora, portátil y de bajo coste para la detección de emisiones de gases de efecto invernadero. Es importante destacar que el sistema demostró ser confiable, capturando con eficacia las fluctuaciones e incertidumbres asociadas, tal como lo demuestran los análisis estadísticos. La implementación amplia de estaciones de medición como las propuestas puede posibilitar la creación de una red de monitorización integral, proporcionando la cobertura y capacidad de respuesta necesarias para hacer frente a los riesgos climáticos actuales.

Originalidad/Valor de la Investigación: Este estudio presenta el desarrollo de un sistema de sensores de bajo coste diseñado para una monitorización ambiental práctica y eficiente. El sistema es adaptable para su uso en grandes áreas, ya sea mediante una red de estaciones fijas o mediante plataformas móviles con drones. Los datos adquiridos durante las mediciones se almacenan y analizan sistemáticamente utilizando estadísticas de “Allan Variance”, procesadas con el *software* OriginPro, garantizando una evaluación robusta de la estabilidad y precisión de los sensores.

Palabras clave: Monitorización de GEI y material particulado, Red de detección con sensores de bajo coste, Monitorización Ambiental, Varianza de Allan, UAVs.

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1 INTRODUCTION

The climate confrontation requires a systemic activity to mitigate anthropogenic processes and to accompany the natural ones that are promoted by various geological processes. Thus, there is a strategic consensus, we need to improve our environmental monitoring systems (Miskell et al. 2018). Carbon dioxide (CO₂) and methane (CH₄) are the most influential long-lived greenhouse gases. Although CO₂ has an effective atmospheric lifetime often estimated to span several centuries, CH₄ is significantly more potent in the short term, exerting more than 25 times the warming effect of CO₂ over a 20-year time horizon. Therefore, CO₂ contributes to long-term cumulative warming, whereas CH₄ exerts a more immediate but relatively short-



lived climate impact (Kiplimo et al. 2024). Since the beginning of industrialization, the globally averaged atmospheric concentration of CH₄ has increased almost continuously, rising from approximately 700 parts per billion (ppb) to nearly 1800 ppb by the end of the 20th century. Several possible explanations have been proposed to account for both the long-term trends and interannual variability in atmospheric CH₄ concentrations. These include fluctuations in the global concentration of hydroxyl radicals (OH), the primary atmospheric sink for CH₄ (Etheridge et al. 1998), as well as changes in emissions from key sources such as rice agriculture, wetlands, biomass burning, and the use of fossil fuel.

In developing countries, where structural limitations and insufficient investment in the environmental sector prevail, the deployment of low-cost sensors emerges as a crucial and feasible solution for effective environmental monitoring. In this work, we propose the common use of a drone and a stationary measurement station for the detection of greenhouse gases and particulate matter. An UAV (Unmanned Aerial Vehicle) was used to identify the main methane emission points, hot spots, in environments such as landfills, river banks or polluted basins. Once identified, this point serves as a base for installing the stationary station to conduct long-term measurements. This study addresses the issue of using low-cost sensors to survey greenhouse gas emissions. Accurate quantification of greenhouse gas emissions requires robust and high-precision measurement techniques (Capone et al. 2003); however, these techniques usually require equipments that are difficult to operate and high cost. The CRDS (Cavity Ring Down Spectroscopy) and flux chambers are the most common reference-grade procedures for tracking greenhouse gases while for Particulate Matter are the Tapered Element Oscillating Microbalance (TEOM) and Beta Attenuation Monitor (BAM) (Bastviken et al. 2020). Simultaneously, large strides in the study of low-cost sensors are setting new performance and miniaturization standards. Particulate matter (PM_{2.5}) concentrations are typically quantified via optical methods, such as light scattering or absorption, with calibration performed through embedded algorithms within the sensor's signal acquisition circuitry (Wang et al. 2015; Raysoni et al. 2023). The resulting attenuated optical signal is then mapped to particle size and concentration. In contrast, gas sensors operate based on either electrochemical interactions or variations in the electrical resistivity of SnO₂ (tin dioxide) sensing elements, induced by exposure to the target analyte within the ambient background gas. Electrochemical gas sensors exhibit high selectivity and sensitivity toward target analytes, enabling detection at ppm or ppb levels. Nonetheless, their operational lifespan is constrained, and their performance can be affected by cross-sensitivity to interfering gases or humidity. In contrast, gas sensors based on non-dispersive infrared (NDIR) technology offer rapid response times, exceptional stability



with minimal signal drift, and high specificity toward target analytes, exhibiting low cross-sensitivity to interfering gases (Hodgkinson, J., & Tatam, R. P. 2013). Two sets of sensors were used in this study: one designed to be mounted on a drone and the other intended for stationary measurements. The drone-mounted system included two NDIR sensors, one for methane (MH-440D, Winsen) and one for carbon dioxide (SCD30, Sensirion), which are factory pre-calibrated modules based on the output method, UART, analog voltage signal. Sulfur dioxide was detected using an electrochemical sensor module (ZE03-SO₂, Winsen). The stationary system was equipped with a laser scattering sensor for particulate matter (PM_{2.5}) (PMS5003, Plantower), an electrochemical sensor for carbon monoxide (ZE07-CO, Winsen), and the same carbon dioxide sensor (SCD30, Sensirion) used in the drone setup. All sensors also included temperature compensation, which enhances their selectivity and stability. In the drone-based configuration, the raw data was collected and stored onboard, without any technical support or ground-based instruments. Therefore both systems incorporate built-in redundancies and complementary functionalities, outfitted with sensors for temperature, relative humidity, and carbon dioxide monitoring. The two systems were integrated, tested and operated in three distinct sites of field work, namely USP, CEPEMA and UFRJ. This article details those activities to describe exactly an operational practice in varying environmental conditions. In our study, is essential to ensure accurate sensor performance avoiding electrostatic faults values and environmental factors such extremely winds as well as storms. Relative humidity (RH) significantly impacts the performance of particle sensors through multiple mechanisms. Firstly, water vapor, similar to certain organic aerosol components (Cho, H., & Baek, Y. 2021), exhibits strong infrared absorption characteristics. This absorption attenuates the light intensity reaching the photodetector, potentially leading to a sensor drift data and/or overestimation of particle mass concentrations in optical sensing systems. Secondly, elevated levels of humidity, particularly under conditions of condensation or saturation, may cause electrical malfunction or degradation of sensor circuitry, thereby introducing systematic errors or measurement biases (Piedrahita et al. 2014). This article evaluates the potential of low-cost sensors as an alternative for monitoring greenhouse gases and particulate matter in contexts where the deployment of reference-grade instrumentation is not feasible. Stability experiments were conducted by measuring the same air sample under stable atmospheric conditions using both sensor sets over several hours. The deployment and testing of the low-cost sensor system in long-term experiments was performed in an open field at USP, State University of São Paulo. During the campaign, these experiments spanned a total of 26 hours. The Allan deviation plot, calculated from these measurements for both sensor sets, is presented. The measurements from



these experiments demonstrate a CO₂ precision better than 20 ppm. The optimization of an algorithm in the operation of the sensors, presented here, was used to reduce energy consumption; every seven seconds, a scan is performed on all the sensors in the set.

2 THEORETICAL FRAMEWORK

The proliferation of alternative boards compatible with Arduino platforms has provided a range of new hardware options with significantly better energy performance for logging applications (Furst et al. 2021). The search for such optimization has led some open-source projects to avoid Arduino boards and create customized printed circuit board solutions around the 328P microprocessor. The use of these options places these devices out of the reach of users with little experience. In this project, we aim to reclaim the simplicity and procedures offered by the Arduino platform, utilizing its operational flexibility, which allows for alternating access to the chosen sensors, thereby minimizing the time dedicated to each of them and optimizing resources by reducing battery consumption. The set of sensors has no dependence on any external system and can therefore be deployed on a variety of UAVs.

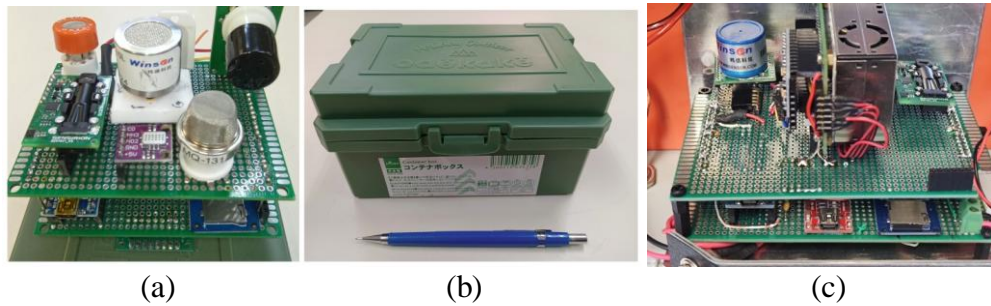
3 METHODOLOGY

A study was initially conducted on the conditioning of several key sensors. The assembly process involved three main protoboards: the sensor board (top), power board (middle), and the power supply & acquisition board (bottom). This setup tested the connections between various components, ensuring that each sensor's data alternated while maintaining a high operating autonomy (Fig.1). The images 1a and 1b display the sensor array integrated with the drone platform (Three primary protoboards and box, total payload: 486 g.), whereas the image 1c illustrate the sensor configuration deployed on the stationary pole mount (810g).



Figure 1

Sensor array components



All measurements were taken inside a protective module carried by the drone or positioned on poles, no additional instruments are required (Beddows, P. A., & Mallon, E. K. 2018). Table 1 summarizes the sensitivity ranges of all sensors over the specified measurement range, accompanied by a comparative analysis of values reported in the corresponding datasheets. This initial test proved the feasibility of carrying out this project, defining the main sensors to be used for monitoring, as well as establishing a payload of 480 g for the drone used.

The project presents a low-cost data logging platform that allows long-term operation in remote or harsh environments. In this first test three “breakout boards” from the open-source Arduino ecosystem are mounted on the core of the data logger. Energy-saving techniques are presented that extend the operational life of this module-based design to 48 hours, with four 7.3 V Li-18650 Li-ion batteries.

Table 1

Summary of published datasheets and comparative studies on the sensitivity ranges of each sensor.

	0,001	0,01	0,1	1	10	100	1000	10000
CO ₂ (ppm)						(-----	-----	-----)
CH ₄ (ppm)		(-----	-----	-----)				
SO ₂ (ppb)			(-----	-----	---			
RH(%)						(-----	-----	-----)
T(°C)					(-----	-----)		
CO(ppm)					(-----	-----	-----)	
PM(µg/m ³)			(-----	-----	-----)			

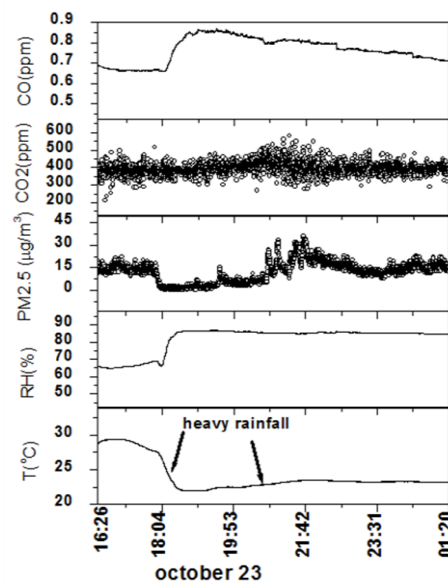


4 RESULTS AND DISCUSSIONS

The first measurement sequence was carried out in the vicinity of the IPEN/MB-01 nuclear reactor, installed at the Nuclear and Energy Research Institute (IPEN), within the capital campus of the University of São Paulo (USP). The purpose was to characterize, over the course of five weeks, the concentrations of gases in the environment alongside biological markers that are being cultivated for studies involving neutron activation analysis techniques. This sequence also served as a test of the conditioning of the sensors' protective boxes, which were exposed to rain, wind and all kinds of inclement weather as part of the field test within a restricted access environment (Fig.2).

Figure 2

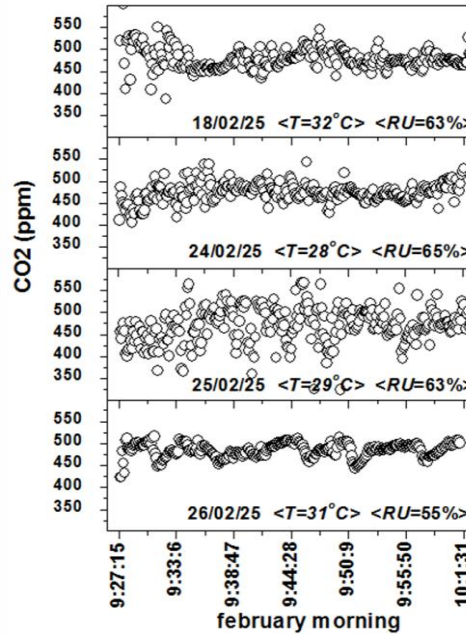
Measurements taken during the reactor campaign at IPEN, along with the installation in a pole at a height of 2 meters, exposed to open sky.



The drone experiments were conducted in the same area at an altitude of 25 meters, with each session lasting 30 minutes over a seven-day period (February 18–26, 2025, Fig. 3). Measurements were taken at 8:30 a.m. and 5:00 p.m. (corresponding to peak traffic hours) within the USP campus, near the Pinheiros waterfront (the floodplains of the Pinheiros River), an area known for its heavy vehicle flow throughout the day. The dispersion of CO₂ concentrations between February 25 and 26 was particularly notable. Despite similar average temperatures, variations in relative humidity appeared to influence the spread of CO₂ data, with the dispersion pattern aligning with changes in humidity levels.

**Figure 3**

Raw data measurements from the Sensirion CO₂ sensor and averaged meteorological parameters collected during the drone experiment.

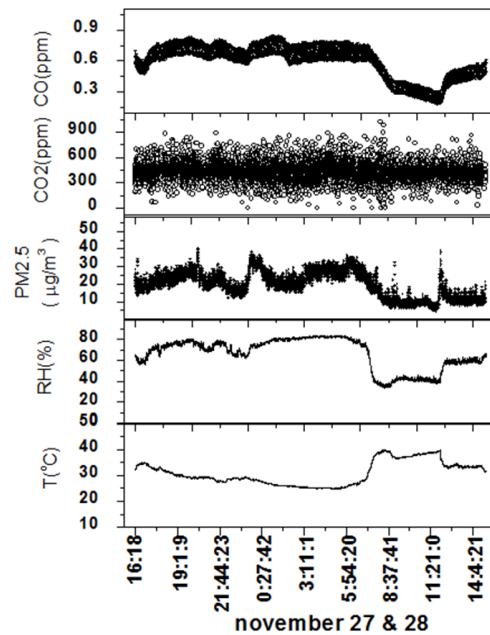


The second measurement sequence was carried out at the Environmental Research Training Center (Cepema, Fig.4) of USP's Polytechnic School (Poli). Cepema is placed at the industrial area of Cubatão in the State of São Paulo (Brazil), characterized by many refineries around; moreover, it is the epicenter of them and home to a Technology Pole of the Oil and Gas Industry, as well. All the atmospheric measurements were performed at ground level at the Cepema and took place in a principal building region avoiding both, winds and solar rays. The sensitivity of the CO₂ and CO sensors reflects the impact of climatic variations, particularly when the rain stopped, from 8:30 to 11:20 am, as recorded in the meteorological data (RH and temperature). During this period, CO₂ dispersion decreased, while there was a clear decrease in CO concentration. For example, the first and second experiments on November, 28th and December, 11th 2024 were performed in the intervals 2:04–6:56 p.m. (UTC–5 h) and 2:06–7:57 p.m. (UTC–5 h), respectively aiming to measure SO₂, CO₂, CO and CH₄ and soot (PM_{2,5}), as well.

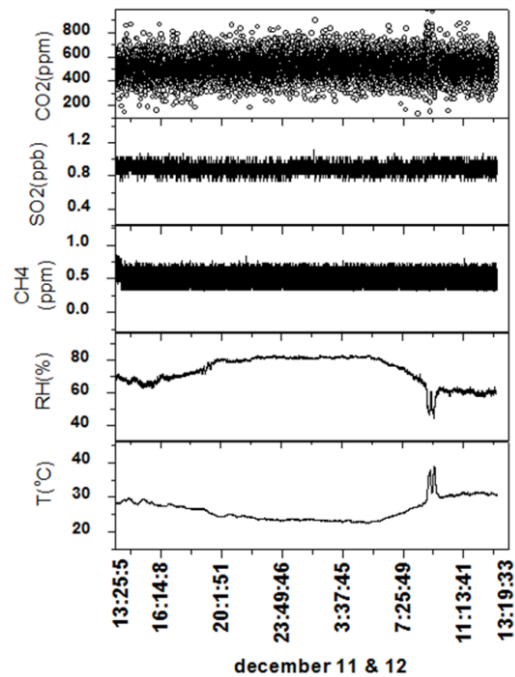


Figure 4

Cubatão campaign measurements taken from the ground, sheltered from rainfall and winds.



Some measurements suggest that the particulate matter and CO sensors still seem to have reliability issues, likely due to their sensitivity range not aligning well with the environmental conditions at the chosen monitoring sites. The sensor might be unable to detect variations accurately in the current atmospheric conditions (Kim et al. 2018). On the other hand, CO₂, CH₄, SO₂ and humidity sensors are performing much better in the specific environments chosen for the monitoring. Their sensitivity and range are suitable for accurately tracking the levels of these gases and parameters in the chosen sites. The climate conditions temperature, percent relative humidity, pressure were also acquired during every data collection. Study area emissions exhibited significant variability throughout the day. On both days of each experiment of the study period, emissions peaked during midafternoon hours due to oil and gas facility activity.

**Figure 5***Measurements from the second Cubatão campaign.*

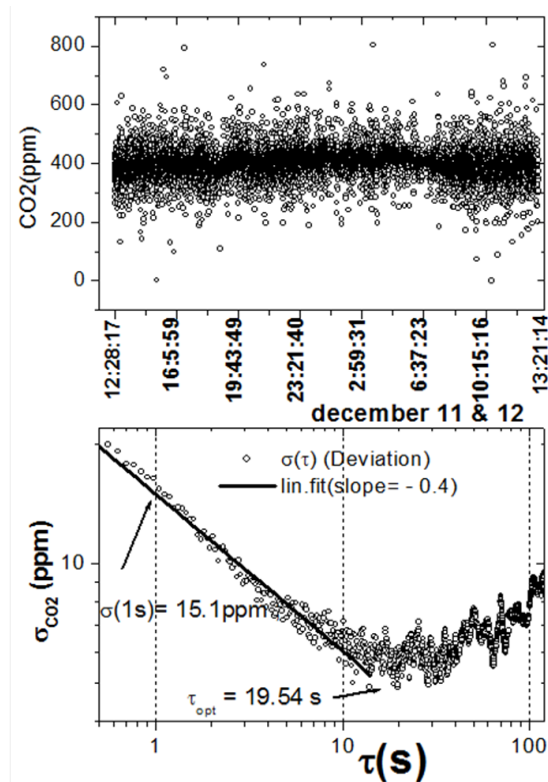
The measurements were conducted over 3 days in each experiment, starting at noon and finishing about 11:30 each day. This time interval assured that the thermal inversion could be completely covered. The measurements in the evening were conducted to determine the background characteristics. We assessed the tolerances in the study of CO₂ concentration signal stability, focusing on characterizing the precision and consistency of signals over time. Allan variance was employed to analyze the time-series data, particularly useful for examining the noise and stability of measurements. This method is especially valuable when working with sensor data, such as CO₂ concentration measurements, as it offers insights into the signal's behavior across various averaging periods and helps identify different types of noise (white noise, random walk and flicker noise). The linearly decreasing part of the Allan deviation is white-noise dominated, and in this part is equivalent to the value of the statistical variance. Since the CO₂ signal in Fig. 6 resembles to be stationary, the Allan deviation helps determine the time interval over which the data can be averaged before drifts become dominant. Long-term measurements for 400 ppm CO₂ were conducted for ~ 25-hour interval. The Allan deviation were performed and presented as insets in Fig. 6, yielding a sensitivity of 15.1 ppm at an averaging time of 1.0 s. The Allan deviation value at a given averaging time provides an accurate estimate of the concentration fluctuations averaged over that period. Additionally, the point at which the Allan deviation begins to increase indicates the stability time. Plotting the



Allan deviation against the averaging time generates the Allan deviation curve, which reveals information about the magnitude of noise present in the raw data. The longer the measurement time for a given data point, the more accurate the result (Kunz et al. 2018).

Figure 6

Measurement of a 400 ppm CO₂ background concentration and its “Allan-Plot” as a function of integration time, presenting a sensitivity of 15.10 ppm at an effective integration time of 1s. The minimum reveals that the highest sensitive measurements can be obtained with a 19-second integration time (τ_{opt}).



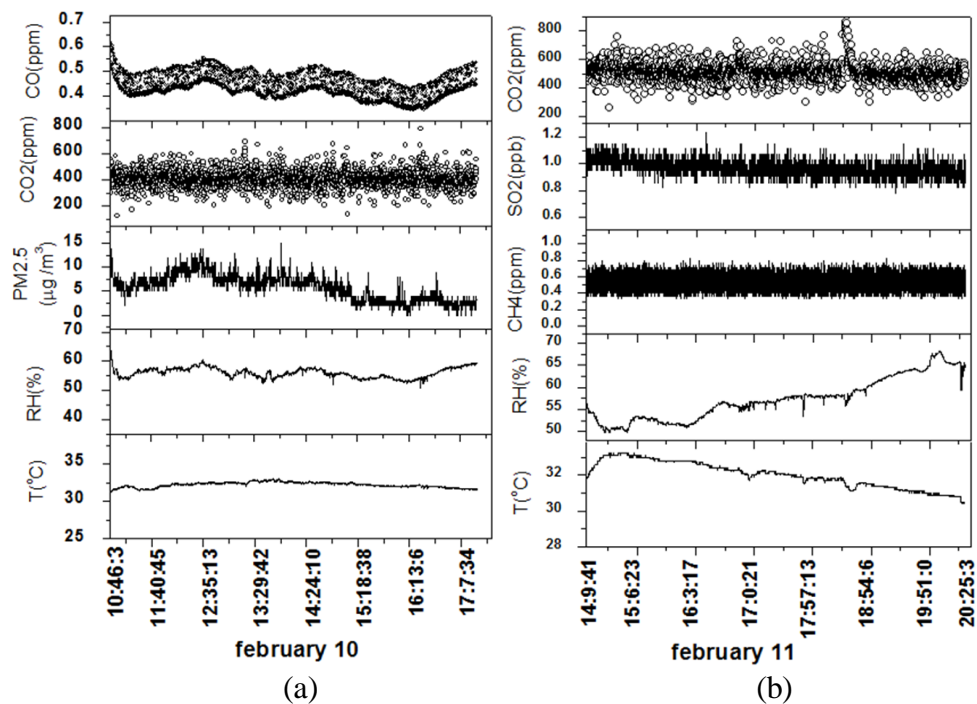
Generally, the Allan deviation decreases as the averaging time increases. However, depending on the instrument, extending the averaging time may lead to instrument drift, which can cause the Allan deviation to rise. Consequently, the optimal averaging time can be determined. The graph of the Allan deviation shows the improving stability of a system as the averaging time τ gets longer, changing from the white phase noise (τ^{-1}) via the white frequency noise ($\tau^{-1/2}$) and the flicker noise (τ^0) to the random walk ($\tau^{1/2}$). The detection limit of the sensor sensation was 15.10 ppm of CO₂ for a 1 s average, this means that white noise, as indicated by the slope of linear fitting, is the dominant deviation term for $\tau < 10$ s.



The Physics Institute of Federal University of Rio de Janeiro (UFRJ) is currently part of the Center for Mathematical and Natural Sciences (CCMN-UFRJ). It is located on FUNDÃO Island on the shores of Guanabara Bay, a region with a constant flow of pollutants and considered to be the most important estuarine system in the state of Rio de Janeiro, with a water mirror of approximately 380 km². Recent studies have been able to identify stagnant areas where the natural hydrodynamic circulation of the system is not enough to dilute the pollution or to disperse it away from the coast. The measurements (Fig.7a and 7b) were conducted over 3 days, starting at noon and finishing about 8:30 p.m. each day.

Figure 7

(a) Fundão campaign measurements taken from the ground, sheltered from rainfall and winds. Measurements of meteorological parameters remained almost constant, which resulted in better-behaved data from the carbon monoxide sensor. (b) On the second day of the Fundão campaign, measurements were taken from the afternoon until the night. The meteorological parameters showed a decrease in temperature, while CH₄ and SO₂ concentrations remained almost constant throughout.



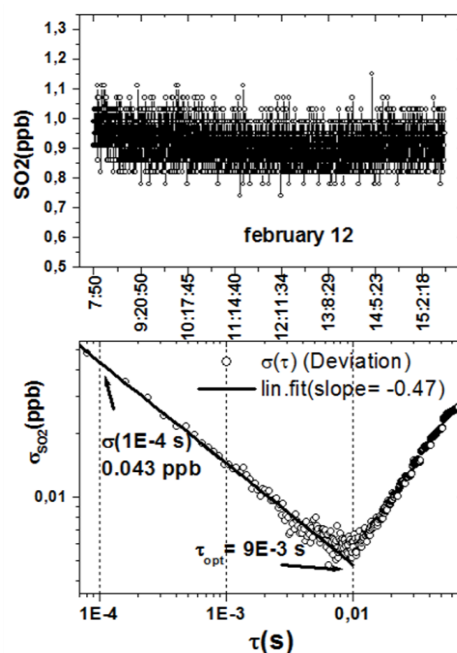
On the last day of the campaign, the experiment was carried out from morning until mid-afternoon. To assess instrument stability, Allan deviation was computed from measurements collected over a 7-hour interval characterized by exceptionally low variability in



background atmospheric SO₂. This measurement interval was selected to suppress the influence of ambient atmospheric variability, thereby providing the stable conditions required to decouple and evaluate the instrument's intrinsic noise characteristics. The SO₂ signal (Fig. 8) remained stable enough to allow testing of the Allan deviation plot, which was instrumental in identifying the optimal time interval for averaging the data before drifts became prominent. The integration time (τ) provided a perspective on the effects of smaller time samples, constrained by the use of batteries (Bonne et al. 2023). The details of Allan deviation, calculated from experiment, are presented in Figure 8. The precision of our measurements can be derived from experiment with background concentration as low as 0.9 ppb: for SO₂, precisions are below 43 ppt at integration time $\tau \sim 10^{-4}$ s. A minimum in precision is observed at $\tau_{\text{opt}} \sim 10^{-2}$ s, beyond which performance exhibits saturation with increasing averaging time.

Figure 8

Fundão campaign measurement of a 0.9 ppb SO₂ background concentration and Allan deviation as a function of integration time, presenting a sensitivity of 43 ppt with integration time of 10^{-4} s.



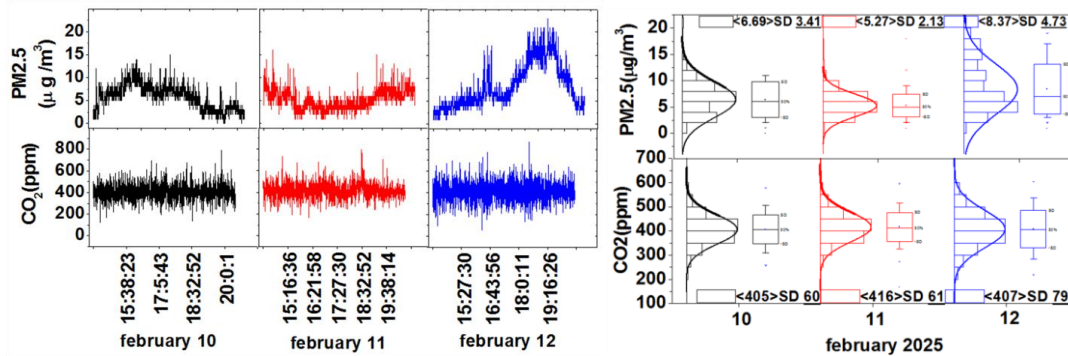
The sensitivity of the measurement system is highlighted by the data collected from two sensors based on different operating principles: the CO₂ sensor and the PM_{2.5} Plantower (Fig. 9 - left). A significant dispersion in the recorded values is observed on the third day in datasets, a trend that is further validated by the deviation statistics and the corresponding count distribution curve (Fig. 9 - right). Concerning the quantification of PM_{2.5} and CO₂ emissions,



the statistical deviation indicated a growing trend in data dispersion observed on the third day. Specifically, PM_{2.5} concentrations reached 8.37 $\mu\text{g}/\text{m}^3$ with a standard deviation of 4.73 $\mu\text{g}/\text{m}^3$, while CO₂ levels measured 407 ppm with a standard deviation of 79 ppm.

Figure 9

Fundão campaign measurement of the CO₂ sensor and the PM_{2.5} Plantower. On the third day, the measurements revealed an increase in data dispersion for both the CO₂ and particulate matter sensors, as evidenced by a corresponding rise in statistical deviation.



5 CONCLUSION

In both arrangements, stand-alone and drone sensor sets, it was demonstrated that the system and method proved effective in monitoring GHG emissions, particulate matter, and meteorological parameters from environments under completely different conditions, including an industrial center with refineries, a megalopolis with heavy traffic, and an island situated in a polluted basin. The stationary measurements can be easily implemented by performing long-term operations, while dynamic measurements using a drone were performed over five consecutive days with 25-minute flights (and a payload of 485 g), logging CH₄ and CO₂ concentrations, as well as RH and temperature, every seven seconds in both cases. All measurements were made on board, without the need for any ground-based instrumentation. The sensor network was tested in the field to continuously monitor CH₄, CO₂, SO₂, PM_{2.5}, and CO concentrations at three different sites near traffic or industrial areas for several hours. Measurements were taken under varying humidity conditions to ensure resistance to weather fluctuations and to maintain quality assurance. Proceeding efforts to enhance the accuracy of these sensors, particularly in understanding their sensitivity to relative humidity, should continue to ensure more precise emissions measurements. In the next phase, we plan to expand the number of stationary monitoring stations. The retrieved GHG concentration values were



consistent with the daily averages reported by the local air quality agency, demonstrating that the developed prototype is reliable for highly sensitive sensor applications.

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