Low-cost sensors for particulate matter measurement

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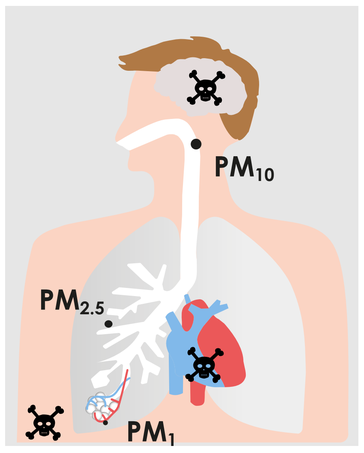
INTRODUCTION

Particulate matter (PM) is a global threat to human health, associated with respiratory, cardiovascular, and neurological diseases, as well as premature mortality. PM toxicity depends on several factors, size being a crucial determinant. PM_{10} (<10µm), typically remains in the upper tract and is less hazardous than $PM_{2.5}$, which can penetrate deeper into the lungs and PM_1, which can enter the bloodstream. Accurate measurement of fine PM is critical, and low-cost sensors (LCS) represent a cost-effective complement to official monitoring networks. This feasibility study aims to compare the performance of a Wi-Fi and two LoRaWAN air quality stations (AQ stations) using LCS to measure PM, with the goal of determining whether the LoRa AQ stations can deliver accurate measurements.

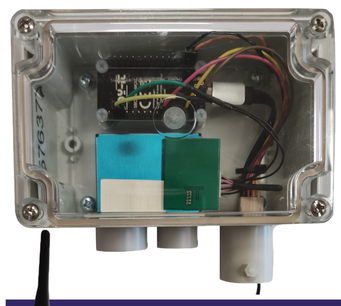


MATERIAL & METHODS

1. Prototyping

A first Wi-Fi AQ station was designed and calibrated with a reference monitor (REF) from Atmo Auvergne Rhône-Alpes. This Wi-Fi AQ station performed well in measuring fine PM [1]. Then a LoRaWAN AQ station was developed to eliminate the dependence on Wi-Fi and allow broader deployment. Both stations were equipped with different temperature (T) and relative humidity (RH) sensors. BME280 should perform better than DHT 22 in high-humidity situations. The firmware used for the Wi-Fi AQ station was developed by sensor.community (https://firmware.sensor.community/airrohr/flashing-tool/) and enabled reporting of PM_1, $PM_{2.5}$, PM_{10}, T, and RH. For the LoRaWAN AQ stations, a novel firmware using RIOT OS (https://github.com/RIOT-OS/RIOT) was developed (https://github.com/airqualitystation/firmware_for_bmx280_pms7003), allowing the extraction of additional parameters, particularly PM counts within different size ranges.

Wi-Fi AQ station

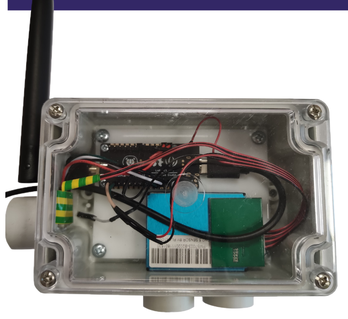


Variables : PM_{10}, $PM_{2.5}$, PM_1, RH, T

Frequency : Every 150 s

Component	Price (€)
PMS7003 (PM sensor)	23,8
DHT22 (RH & T sensor)	10,9
NodeMCU ESP8266 microcontroller	12,3
Polycarbonate IP66 outer case	15,9
Euromas II wall brackets	3,2
USB / USB-A 2m flat cable	11,9
5V USB power supply	6,9
	84.9

LoRaWAN AQ station



Variables : PM_{10}, $PM_{2.5}$, PM_1, RH, T, pressure, particles count (>0.3 µm, >0.5 µm, >1 µm, >2.5 µm, >10 µm)

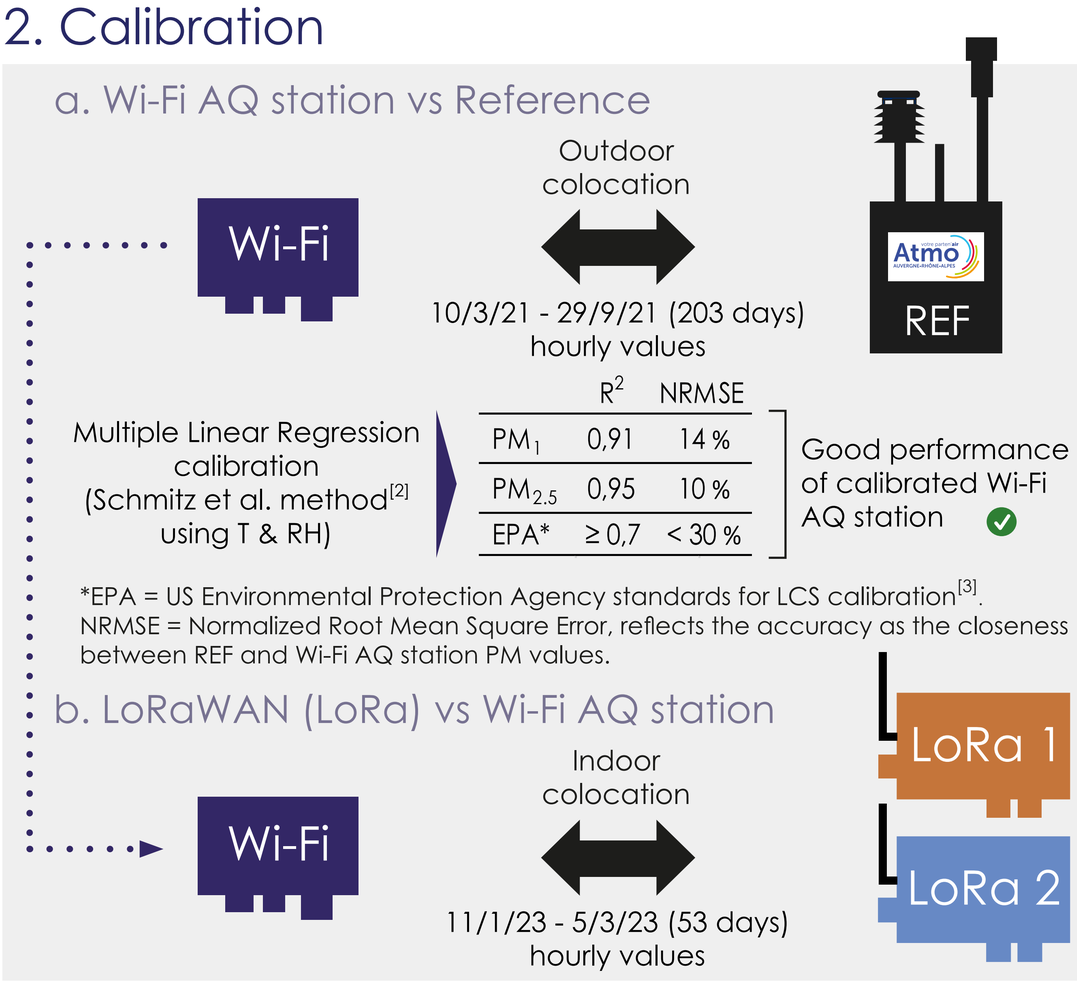
Frequency : 8 s median (99,4 % of time intervals < 150 s) *

Component	Price (€)
PMS7003 (PM sensor)	23,8
BME280 (RH & T sensor)	19,9
LoRa-E5 mini board	27,9
Polycarbonate IP66 outer case	15,9
Euromas II wall brackets	3,2
USB-C / USB-A 3m flat cable	14,9
5V USB power supply	6,9
	112,5

* According to ESTI regulation, the measurement period is adapted to the datarate depending on the range between the LoRaWAN AQ station & the gateways (5 to 160 s).

2. Calibration

a. Wi-Fi AQ station vs Reference



Multiple Linear Regression calibration (Schmitz et al. method[2] using T & RH)

	R^2	NRMSE
PM_1	0,91	14 %
$PM_{2.5}$	0,95	10 %
EPA*	≥ 0,7	< 30 %

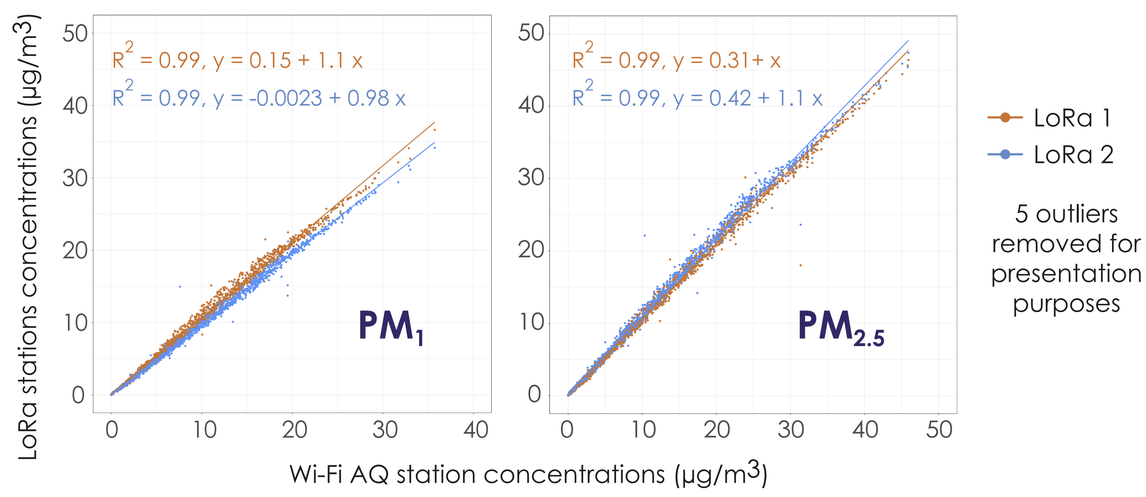
Good performance of calibrated Wi-Fi AQ station

*EPA = US Environmental Protection Agency standards for LCS calibration[3].
NRMSE = Normalized Root Mean Square Error, reflects the accuracy as the closeness between REF and Wi-Fi AQ station PM values.

b. LoRaWAN (LoRa) vs Wi-Fi AQ station

RESULTS

1. LoRaWAN performance vs. Wi-Fi AQ station



➡ R^2, slope & intercept conform to EPA standards ✅

➡ Additional metrics :

	NRMSE (%)	SD (µg/m³)	CV (%)
PM_1	9	0,7	6,6
$PM_{2.5}$	11	0,6	4,2
EPA	< 30	< 5	≤ 30

LoRaWAN AQ stations : sensor - sensor precision ✅

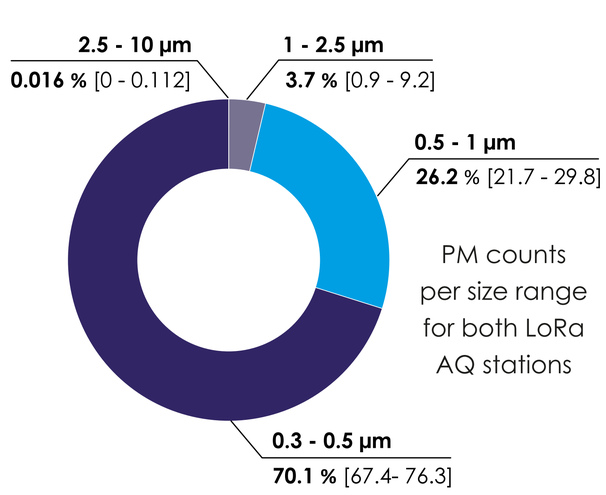
SD: standard deviation
CV: coefficient of variation

+ NRMSE Wi-Fi / REF (refer part 2.a)

PM_1 : NRMSE = 23 %
$PM_{2.5}$: NRMSE = 21 %

LoRaWAN AQ stations : sensors accuracy vs REF ✅

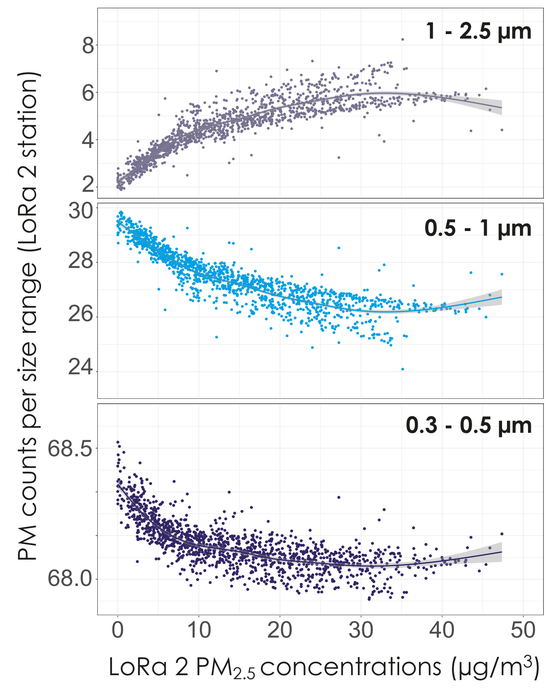
2. Particle counts



PM counts per size range for both LoRa AQ stations

➡ PM mainly submicron

➡ When $PM_{2.5}$ concentration increases, the percentage of submicron PM decreases while that of larger PM increases



CONCLUSION

- LoRaWAN AQ stations performance metrics conform to EPA standards.
- LoRaWAN AQ stations deliver precise & reliable particulate matter measurements.
- The firmware allows particles counts extraction, which will be useful for further research.

REFERENCES

1. Aix ML, et al. (2023). Calibration Methodology of Low-Cost Sensors for High-Quality Monitoring of Fine Particulate Matter [Manuscript under revision]. 2023.

2. Schmitz S, et al. (2021). Unravelling a black box: An open-source methodology for the field calibration of small air quality sensors. Atmos. Meas. Tech. 4:7221–41.

3. Duvall R, et al. (2021). Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors: Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications. EPA/600/R-20/280. US Environmental Protection Agency, Office of Research and Development.