Comparison of Micro-sensors to Regulatory Instruments for the European Air Quality and Mobility (AQMO) Project

Manuel Chevé, Simon Leray, Maël Jan, David Lavoué

1. Introduction

Particulates matter are well-known regarding the human health negative impact. Mostly in cities, transportation sector is one of the main important PM emitting contributors. Current regulation requires conducting long-term measurements with reference instruments. However, for the past few years, air quality monitoring agencies have started to complement their networks of reference instruments with micro-sensors. The cost of these sensors vary from a few hundreds to a few thousands of euros, i.e. one order of magnitude less expensive than those reference instruments.

Measurements from micro-sensors can provide detailed spatial and temporal air quality data to complete existing operational monitoring network. Some current studies are focusing on developing methods to assimilate concentrations measured by micro-sensors into air quality models (e.g., thesis from Ecole Centrale de Lyon).

Results from previous inter-comparison experiments with reference instruments have indicated that sensors are not as accurate and as precise as regulatory equipment.

The AQMO project consists of micro-sensors installed on mobile units. So, thanks to, this project in which Air Breizh is proud to participate, Air Breizh decided to test several micro-sensors to measure hourly concentrations, check their ability to capture pollution events, characterize sensors' behavior in the real-world and quantify deviation from reference observations. Air Breizh is a newcomer in the field of micro-sensors and relies on this project to increase its experience and competence in this field.

2. Experimental Design

Air Breizh decided to install several types of sensors at two operational sites for an extended duration in order to validate their data against reference measurements and to compare sensors against each other.

2.1. Measurement Sites

The objective of our study is to compare micro-sensors to reference instruments installed at two air quality stations in Rennes: an urban background station located in a small park along Pays-Bas Avenue and a traffic station along the René Laennec Boulevard (Figure 1).

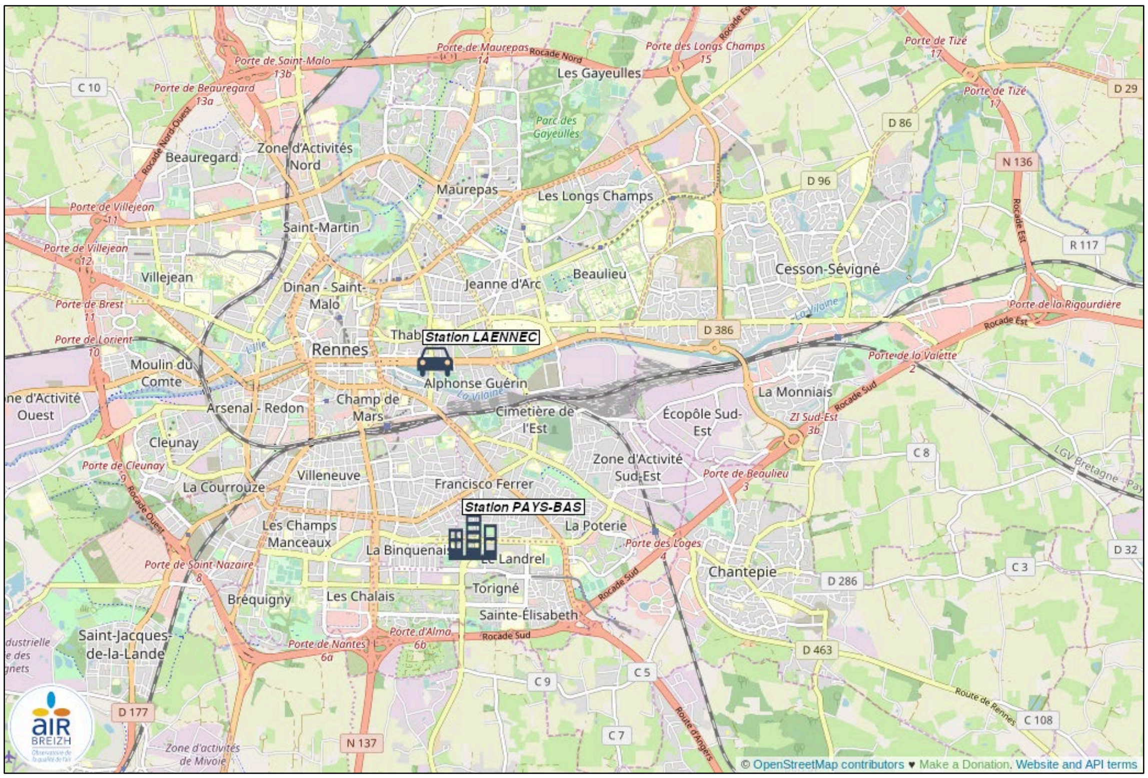

Figure 1: The two continuous air quality monitoring stations ("Pays-Bas", "Laennec") operated by Air Breizh and selected as reference sites for the AQMO study (map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org).

The intervention on these stations needs to be programmed with the technical service with expert speakers in these stations. Under normal circumstances, these stations being located in Rennes, this does not pose any problems, but the end of 2019 and 2020 saw this normality shattered with the "covid" constraint.

These stations allow the temporary installation of weatherproof measuring equipment by relying on masts or existing shelter.

2.1.1. Measurement site known as "Pays-Bas"

The urban background station "Pays-Bas" at Rennes is part of the French measurement network CARA (in French : "*Caractérisation chimique des particules*[1]"). CARA's objective is to determine the main sources of ambient particles under normal conditions and during pollution episodes. For this purpose, the CARA sites integrate various types of instruments to measure PM concentrations and composition.

Station "Pays-Bas" is equipped with a FIDAS to measure ambient levels in PM_1, $PM_{2.5}$, PM_{10} and total PM. It has mainly been used to experiment how to plug and get data from sensors. In the next sections, all mentioned data have been get from sensors deployed at road-side air quality station "Laennec" (also in Rennes).

2.1.2. Measurement site known as "Laennec"

With respect to the road-side air quality station, a common reference technique for monitoring PM includes the Beta Attenuation Monitor (BAM) which measures properties of PM directly related to its mass.

Figure 2: Location of the street-side cabin sheltering the measurement instruments (indicated by the yellow circle) on René "Laënnec"Boulevard in downtown Rennes.

Figure 3: BAM instrument at "Laennec".

A weather shelter has been specifically installed at this station in order to accommodate micro-sensors (or other equipment) not protected from the weather.

This was the main station for AQMO experiments.

[1] Chemical characterisation of particles

2.2. Technical specifications of the micro-sensors

We conducted an evaluation of various micro-sensors against traditional monitoring equipment. PM micro-sensors infer PM mass by detecting particles by number.

2.2.1. Used micro-sensors but not selected for AQMO

<u>SDS011</u>

Although the SDS011 sensors were not selected for AQMO project, Air Breizh decided to include them in their scope in order to increase some internal basic electronic and engineering skills. Indeed, this system needs to be entirely built from bare components (PM sensor, Temperature and humidity sensor, controller) and acquired experience from was so important for AQMO project.

<u>Figure 4</u>: detail of one initial SDS011 sensor box (left), three of them in the meteorological shelter at «Laënnec» (center), New experimental package with two associated sensors are (right) to be able to evaluate some bias.

New SDS011 packaging prototype shown in figure 6 (right picture) have been deployed for unit tests during 2020 summer and one of them at station "Laennec", the 11th of November. This kind of packaging are less smart as AQMO one (with OPC-N3 sensors) because they contain only pollutant, moisture and temperature data acquirement by wifi transmission capabilities without all remote administration and connectivity capabilities that IRISA has integrated in its own package.

<u>Atmotrack</u>

Atmotrack is a 'out-of-the-box' system from Nantes' startup : '42 Factory'.
In France, Atmotrack is known as one of the first air quality micro-sensors fleet deployment firm.
They provide some easy-to-use packaged micros-sensors and an API to get data from sensors.
Contrarly to SDS011 system, Atmotrack system is ready to plug but all the needed sensors are rented.

<u>Figure 5</u>: Atmotrack at "Laennec" and detail of one of them.

2.2.2. Alphasense OPC-N3

OPC-N3 is the identified PM sensor to equip buses in AQMO project. In the same way as SDS011, it needs to be included in a fully DIY built package. In case of AQMO project, packaged box and architecture (electronic and embedded program) has been developed by IRISA. Air Breizh has worked on a specific ‘Raspberry Pi’ package in order to increase its internal skills but has used IRISA’s box to get data at station “Laennec” in order to evaluate the sensor used in AQMO project.

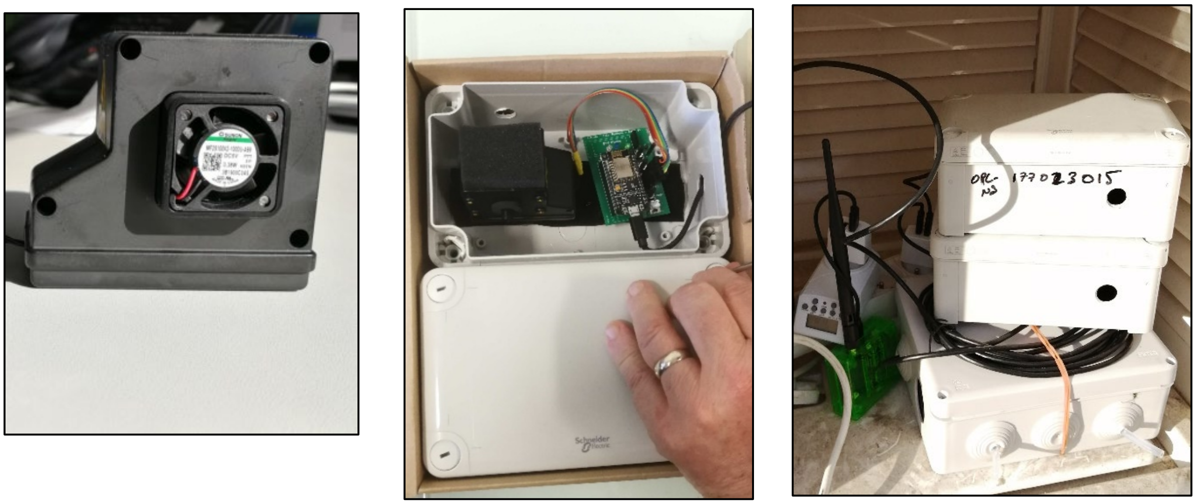

Figure 6: Detail of one Alphasenses OPC-N3 sensors (left), detail of IRISA packaging (right) and two OPC-N3 in their box at “Laënnec” (center).

2.2.3. FIDAS Frog

Fidas Frog is a handled instrument from Addair[2] designed to offer an easy way to get real-time PM measurements. It is used, in particular, in French car industry to evaluate PM levels inside vehicle cabin. Fidas Frog is mainly dedicated to indoor and workplaces measurement, even if, outdoor use is also mentioned by PALAS[3]. Air Breizh had tested Fidas Frog instrument on operational conditions in 2020 during a study focus on air quality in the landfill center of Saint-Brieuc Armor Agglomération[4].

Figure 7: The FIDAS Frog was placed in the meteorological shelter at «Laënnec».

2.3. Experimental Setup

[2] http://www.addair.fr/product/analyseur-temps-reel-portable-poussieres-fidas-frog/

[3] https://www.palas.de/en/product/fidasfrog

[4] not published yet

The table below (table 1) gives main information about the micro-sensors used.

Sensor model	SDS011	Atmotrack	OPC-N3	Fidas Frog
Manufacturer	Nova Fitness	42 Factory (integrator)	Alphasense	Addair
Approximate price (€)	40	260 € (Monthly rental)	500	-
Dimensions (mm)	71x70x23	140x140x46.5	75x60x63.5	240x150x100
Weight (g)	50	500	105	2100
Power supply voltage	5	DC 12	DC 4.8 to 5.2	Lithium battery + AC/DC 220
Working current (A)	0.22	1	0.18	
Detectable size range (µm)	0.3- 10	0.3 - 1.0 1.0 - 2.5 2.5-10	0.5 to 40	
Estimated PM concentration	$PM_{2.5}$ / PM_{10}	PM1 / $PM_{2.5}$ / PM_{10}	PM1 / $PM_{2.5}$ / PM_{10}	PM1 / $PM_{2.5}$ / PM_4 /PM_{10}
Concentration Range (µg/m³)	0-999.9	0 - 500	0-2000	0-10000
Identifiers	532146 (#1) 77899817 (#2) 7789987 (#3)	134 (#1) 148 (#2) 149 (3)	177010415 (#1) 177023015 (#2)	
Station "Pays-Bas" period	-	2019-01-16 to 2019-02-21	-	-
Station "Laennec" period	2019-06-20 to 2019-07-12	2019-02-21 to 2019-06-28	2020-07-10 to 2020-12-01	2019-07-10 to 2019-07-16

Table 1: Characteristics of the sensors selected for this study.

One of the main difficulties during the project was to succeed in the convergence of Air Breizhs' and IRISAs' calendars. Indeed, on one hand, Air Breizhs' technical team has to manage almost 20 stations all around the Brittany and on the other hand, IRISA team has to manage its own bonds and contingencies. Moreover, the two confinements imposed by the covid epidemic made the interactions more difficult. As a result, it was quite impossible to plan the sensors availability in "Laennec" and "Pays-Bas" air monitoring stations and **we finally have focused on comparison in Laennec station which have many advantages**.

2.4. Data Analysis

2.4.1. Reference Methods

At station "Laennec", Air Breizh has deployed PM measurement equipment known as BAM-1020 and FIDAS 200. The first one gives the official reference measurement whereas the second is currently being validated.

Figure 12: BAM-1020 (source : Met One Instrument, Inc.)

On one hand, BAM-1020 automatically measures and records airborne particulate concentration using principle of beta ray attenuation. A filter tape is used to perform a beta ray count from a small carbon-14 source at the beginning of each sample hour, and then after 1 hour exposition of the filter tape to a measured and controlled amount of outside air. The difference between the two measures is converted to a PM mass concentration in outside air. **This equipment provides one data each hour**.

On the other hand, FIDAS 200 (not to be confused with FIDAS FROG mentioned above) is an optical aerosol spectrometer which determines particle size by means of scattered light analysis according to Lorenz-Mie. This equipment is deployed at station "Laennec" to determine if it is relevant to measure traffic air pollution in Rennes with it, regarding our reference equipment "BAM-1020" and to determine how it can be used for that. **This equipment provides 4 data each hour.**

Figure 13: Fidas 200 (source : Addair document.)

These facilities are twice mentioned in the document "*Liste des appareils conformes pour la mesure réglementaire de la qualité de l'air*" from the LCSQA national laboratory and used by Air Breizh to perform its reference measurement.

Air Breizh generally uses these reference measurements to compare data from other sensors (micro-sensors for example) to establish the quality of new data acquisition. This is the aim of the next chapters.

2.4.3. Micro-sensor Data Analysis

Different statistical criteria were employed to evaluate sensors against reference measurement :

- Determination coefficient R^2: this coefficient is used to judge the quality of a linear regression. Near from 0, it means that there is no correlation between the two dataset whereas near from 1, it means that data from micro-sensors fit perfectly regulatory data.
- Bias: this indicator describes the fidelity of the model i.e. whether our micro-sensor systematically overestimates or underestimates the regulatory values. The closer it is to 0 the better is the fidelity of the micro-sensor measurements compared to the regulatory measurements
- MFBE (Mean Fractionalized Bias Error): Fractional bias is a normalisation of the value of the bias, thus allowing comparisons to be made, making it easier to interpret the bias. MFBE is between -2 and 2. 0 means that micro-sensors data and regulatory data have the same means. Positive MFBE implies that the micro-sensor underestimates the measurement compared to the regulatory measure whereas negative MFBE implies the opposite.

All these statistical criteria are calculated using Python software created by Air Breizh for its modeling tools and adapted to the needs of the AQMO project.

3. Results and Discussion

First of all, SDS011 and Atmotrack sensors installed in 2019 are not analyzed in this report. Only the OPC-N3 sensor selected and built for the AQMO project is studied.

Reference dataset to compare

The previous chapters have enabled us to come back to the reference measurement methods for fine particles used by Air Breizh. The AQMO project needed to be able to assess the quality of the micro-sensors in a global way. From this point of view, the methodology consists in positioning the micro-sensors in a reference measurement situation, in our case, at the Laennec station in order to compare the measurements made by micro-sensors with those of the BAM-1020 (reference). As station Laennec has a second device undergoing validation, Fidas-200, based on the same measurement system (optical measurements), it has enabled to rely on this second set of "pseudo-reference" data. Finally, a third device has been considered to qualify the measurement of micro-sensors (particularly in mobile environments), the Fidas Frog.

What about Fidas Frog ?

Fidas Frog was positioned from the 10th to the 16th of July 2019 at the Laennec station. The comparison shows an optimal operating rate but a fairly average correlation (R^2 of 0.49 in PM10 and 0.46 in PM2.5), in a summer period where the mass concentrations of PM are very low. This operational campaign did not allow Air Breizh to go further. However, the indoor air quality measure by Fidas Frog will be discussed in the 2020 study focus on the air quality in the landfill center of Saint-Brieuc Armor Agglomération.

Time scope for the OPC-N3 analyses

From the 10th of July to the 27th of November, 45% of hourly average has been lost due to a transmission problem and not to a measurement problem (2.4% / 1% data loss for BAM and Fidas). Nevertheless, since the 19th of November (after an upgrade of the LORA transmission module), this rate has increased up to 90% of acquired data successfully transmitted (data losses are still being observed).

Thus, we will focus on two specific periods on two seasons :

- First period in summer: from 10th of July to 05th of August;
- Second period in autumn: from 19th of November to the 1st of December.

During summer period (July and August), PM mass concentrations have been lower than during autumn (November) period. Indeed, 50% of the values in reference dataset (BAM-1020) are lower than 4 µg/m^3 whereas there are 50% less than 16 µg/m^3 in autumn. According to the low level of PM mass concentrations in summer, it is less relevant to compare the micro-sensors datasets to the reference dataset on this period.

With an average PM hourly mass concentrations in second period 4 times upper than in the summer period, we will focus on the autumn period.

First results from OPC-N3 sensors

Elements presented after are based on statistical results calculated: **(1)** over the total measurement period **(2)** over the summer period **(3)** over the autumn period.

Main observations are:

- Firstly, **two OPC-N3 sensors are well correlated among each other** (R^2 close to 0.9 in PM2.5) **but with a strong bias** (with a MFBE close to 1). There is a systematic bias error: **the OPC-N3 #1 signal underestimates compared to the OPC-N3 #2**
- Secondly, **OPC-N3 sensors underestimates PM2.5 mass concentrations** compared to the BAM-1020 reference dataset. **However, the OPC-N3 #2 signal is more accurate than the OPC-N3 #1 one**.
- Finally, although the OPC-N3 sensor has an optical measurement system equivalent to the Fidas-200 one, **the two OPC-N3 do not reproduce the signal of the FIDAS-200 better than the BAM-1020 one**. The results are slightly better but the gain is not significant (especially in autumn). At the same time, the two regulatory measures are highly correlated with low bias.

(1) Global period

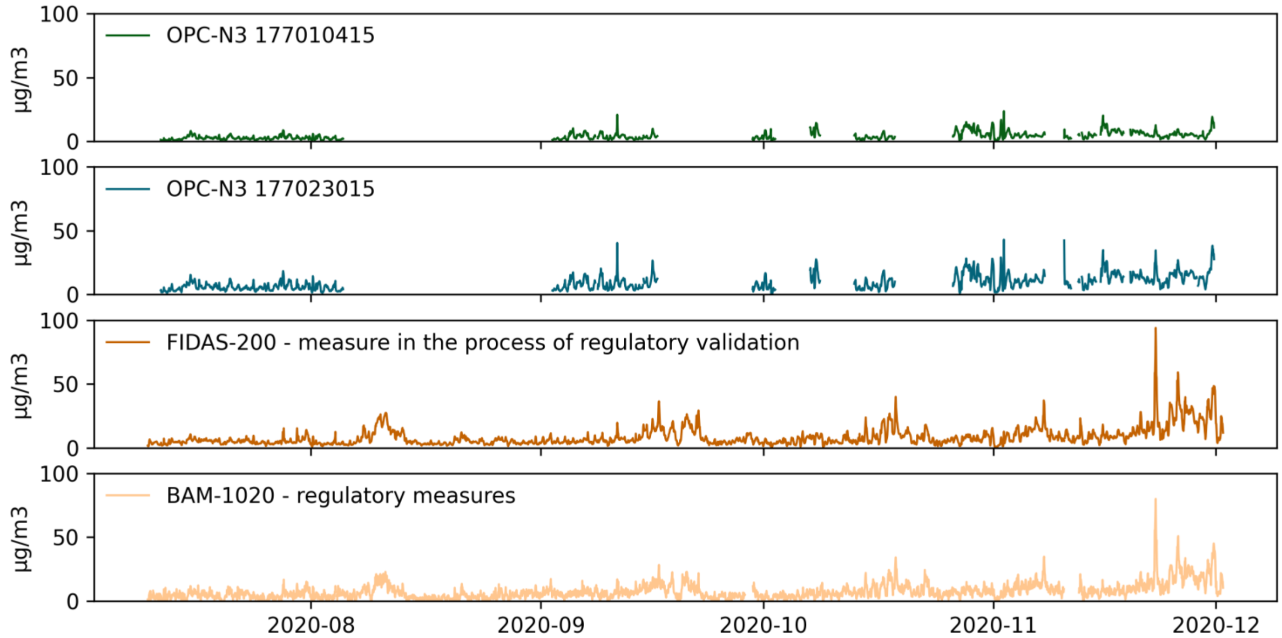

Figure 14: general behavior of OPC-N3 sensors along the whole test period

	OPC-N3(#1)	OPC-N3(#2)	FIDAS 200	BAM-1020
µg/m³				
Mean	2.6	5.8	4.7	4.5
Min	0.4	1.3	0.9	-2.8
Q1 (25 %)	1.6	3.8	3.3	2.5
Mediane (50 %)	2.3	5.3	4.4	4.3
Q3 (75 %)	3.2	7.3	5.7	6.2
Max	8.7	18.4	15.3	16.8

Table 2 : general description of hourly dataset during the first identified period - from 10th of July to 05th of August

	OPC-N3(#1)	OPC-N3(#2)	FIDAS 200	BAM-1020
µg/m³				
Mean	5.4	14.5	21.7	18.0
Min	1.4	4.0	3.7	3.9
Q1 (25 %)	4.0	10.4	12.6	10.5
Mediane (50 %)	4.9	13.5	19.0	15.5
Q3 (75 %)	5.9	16.8	28.1	22.5
Max	19.2	38.3	93.8	80.0

Table 3 : general description of hourly dataset during the second identified period - from 19th of November to 1st of December

(2) First period : from 10th of July to 05th of August

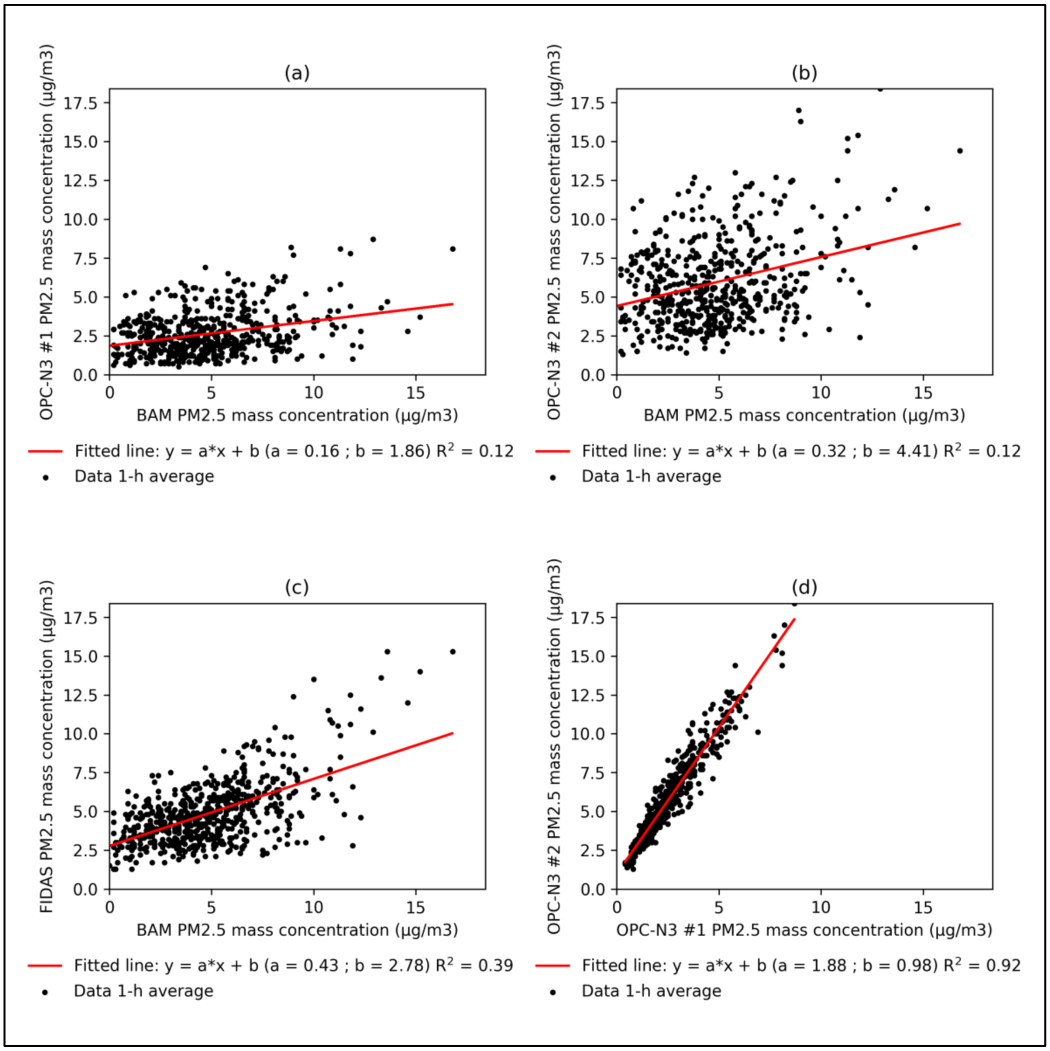

Figure 16: boxplots to evaluate correlation between the two OPC-N3 and BAM (a and b), then BAM and Fidas (c) and OPC-N3 (d) on the first focused period.

	OPC-N3(#1)	**OPC-N3(#2)**	**FIDAS 200**	**BAM-1020**
	$0 < R^2 < 1$: optimal value = 1		$-2 < MFBE < 2$: optimal value = 0	
OPC-N3(#1)				
OPC-N3(#2)	R^2: 0.92 MFBE : 0.78			
FIDAS 200	R^2: 0.38 MFBE: 0.64	R^2: 0.46 MFBE: -0.18		
BAM-1020	R^2: 0.12 MFBE: 0.54	R^2: 0.12 MFBE: -0.26	R^2: 0.39 MFBE : -0.05	

Table 4: OPC-N3 1770110415 (#1) and 177023015 (#2) vs BAM and Fidas regulatory equipment from from 10th of July to 05th of August.

(3) Second period : from 19th of November to 1st of December

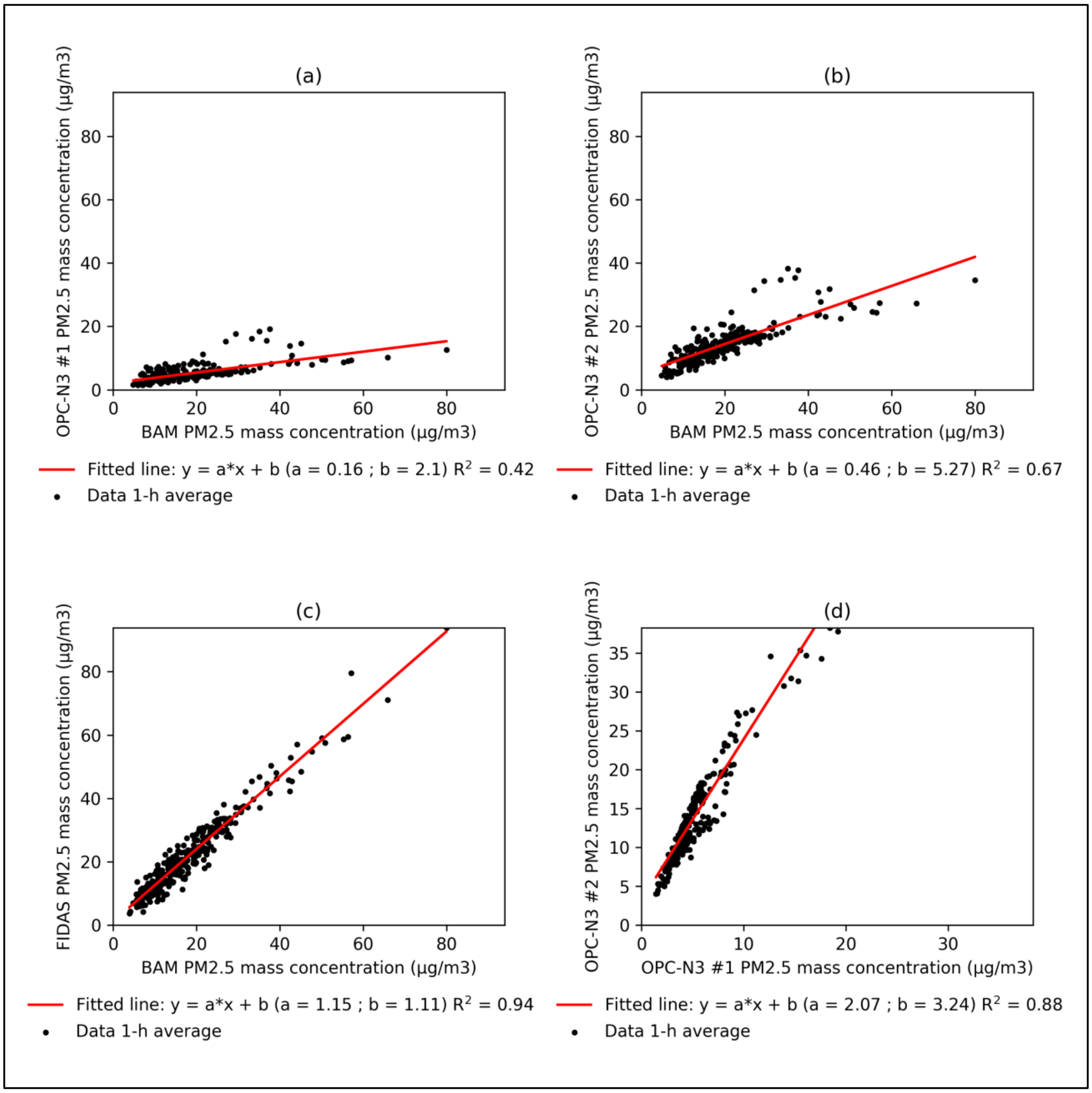

Figure 17: boxplots to evaluate correlation between the two OPC-N3 and BAM (a and b), then BAM and Fidas (c) and OPC-N3 (d) on the first focused period.

	OPC-N3(#1)	**OPC-N3(#2)**	**FIDAS 200**	**BAM-1020**
	$0 < R^2 < 1$: optimal value = 1		$-1 < MFBE < 1$: optimal value = 0	
OPC-N3(#1)				
OPC-N3(#2)	R^2: 0.88 MFBE : 0.91			
FIDAS 200	R^2: 0.43 MFBE: 1.27	R^2: 0.7 MFBE: 0.51		
BAM-1020	R^2: 0.42 MFBE: 1.15	R^2: 0.67 MFBE: 0.32	R^2: 0.94 MFBE : -0.19	

Table 5: OPC-N3 1770110415 (#1) and 177023015 (#2) vs BAM and Fidas regulatory equipment from from 19th of November to now.

4. Conclusions

First of all, data from SDS011 and Atmotrack were not analyzed for the purposes of this report, because they would not be the sensors selected for the 2nd phase of the project. Nevertheless, a quick analysis enabled us to establish first conclusions. Atmotrack should be a good alternative to equip such sensors network but it is quite impossible to have information about the way that the raw data is retrieved and corrected. However, SDS011 is a good "teaching" sensor but not enough efficient for such a measurement network.

The Fidas Frog, unfortunately no comparison between Fidas Frog and OPC-N3 has already been made. And the first comparison between Fidas Frog and reference dataset were not enough to draw conclusions. Results from operational campaign should give more information about the abilities of the Fidas Fog to be an alternative way to qualify micro-sensors in a moving use. Conducting more experimental tests with Fidas Frog equipment could be one of the next steps to confirm or not if it is a good way to qualify the OPC-N3 on the move.

This study, focused on the OPC-N3, has ensured that the micro-sensors have been confronted to the same conditions of pollutant concentrations as devices regulated by the LCSQA laboratory. It is essential to precise that we do not have a sufficient volume of continuous data to be able to perform a deeply analysis. The results could be associated to road traffic and meteorological parameters to go further. Moreover, it could be interesting to apply statistical methods such as the Interquartile Range rule [Moore et al., 2009].

It is important to note that the raw data of OPC-N3 has been directly used, unlike the Atmotrack one is downloaded from a proprietary web portal. To use these OPC-N3 sensors, it would be interesting to further investigate the output data processing, in order to get a more accurate measurement (for example, with external parameters such as temperature and moisture).

Thanks to all the collaborations between the different actors of the project (mainly IRISA and its expertise in electronic and computer integration of micro-sensors, AIR BREIZH concerning the analysis of air quality data), it has been possible to show the level of performance of the OPC-N3 sensors and to show that the whole architecture deployed will allow, in the future, to integrate new measuring devices (such as the next-PM for example, [AIR BREIZH, 2020]).

5. References

Borrego, C., A.M. Costa, J. Ginja, M. Amorim, M. Coutinho, K. Karatzas, … M. Penza (2016), Assessment of air quality microsensors versus reference methods: The EuNetAir joint exercise, Atmospheric Environment, 147, 246–263, https://doi.org/10.1016/j.atmosenv.2016.09.050.

Bulot, F.M.J., S.J. Johnston, P.J. Basford, N.H.C. Easton, M. Apetroaie-Cristea, G.L. Foster, … M. Loxham (2019). Long-term field comparison of multiple low-cost particulate matter sensors in an outdoor urban environment. Scientific Reports, 9(1), 7497. https://doi.org/10.1038/s41598-019-43716-3.

http://www.airlab.solutions/sites/default/files/20181114_Resultats_Tous_Capteurs.pdf (accessed 14 August 2019).

LCSQA (2018), 1er essai national d'aptitude des micro-capteurs (EAµC) pour la surveillance de la qualité de l'air : synthèse des résultats (in French), https://www.lcsqa.org/fr/rapport/premier-essai-national-daptitude-des-micro-capteurs-eamc-pour-la-surveillance-de-la-qualite (accessed 3 September 2019).

Soulhac, L., P. Salizzoni, F.-X. Cierco, and R. Perkins (2011), The model SIRANE for atmospheric urban pollutant dispersion; part I, presentation of the model, Atmospheric Environment, 45(39), 7379–7395, https://doi.org/10.1016/j.atmosenv.2011.07.008

Nguyen, C. V. (2017), Assimilation de données et couplage d'échelles pour la simulation de la dispersion atmosphérique en milieu urbain, Thèse de doctorat de l'Université de Lyon, Ecole Centrale de Lyon, 303 p. (in French).

LCSQA (2007), Liste des appareils conformes pour la mesure réglementaires de la qualité de l'air (in French), https://www.lcsqa.org/system/files/Liste%20appareils%20conforme%20mesure%20_qualit%C3%A9%20air%20M%C3%A0J_v2%2007-02-19.pdf (accessed 24 November 2020)

AIR BREIZH (2020), Evaluation des micro-capteurs next-PM/NEMo TERA Environnement , Campagnes de mesures janvier/février 2020 (in French), https://www.airbreizh.asso.fr/voy_content/uploads/2020/05/air-breizh-rapport-capteur- next-pm-tera-v050520.pdf (accessed 30 November 2020)