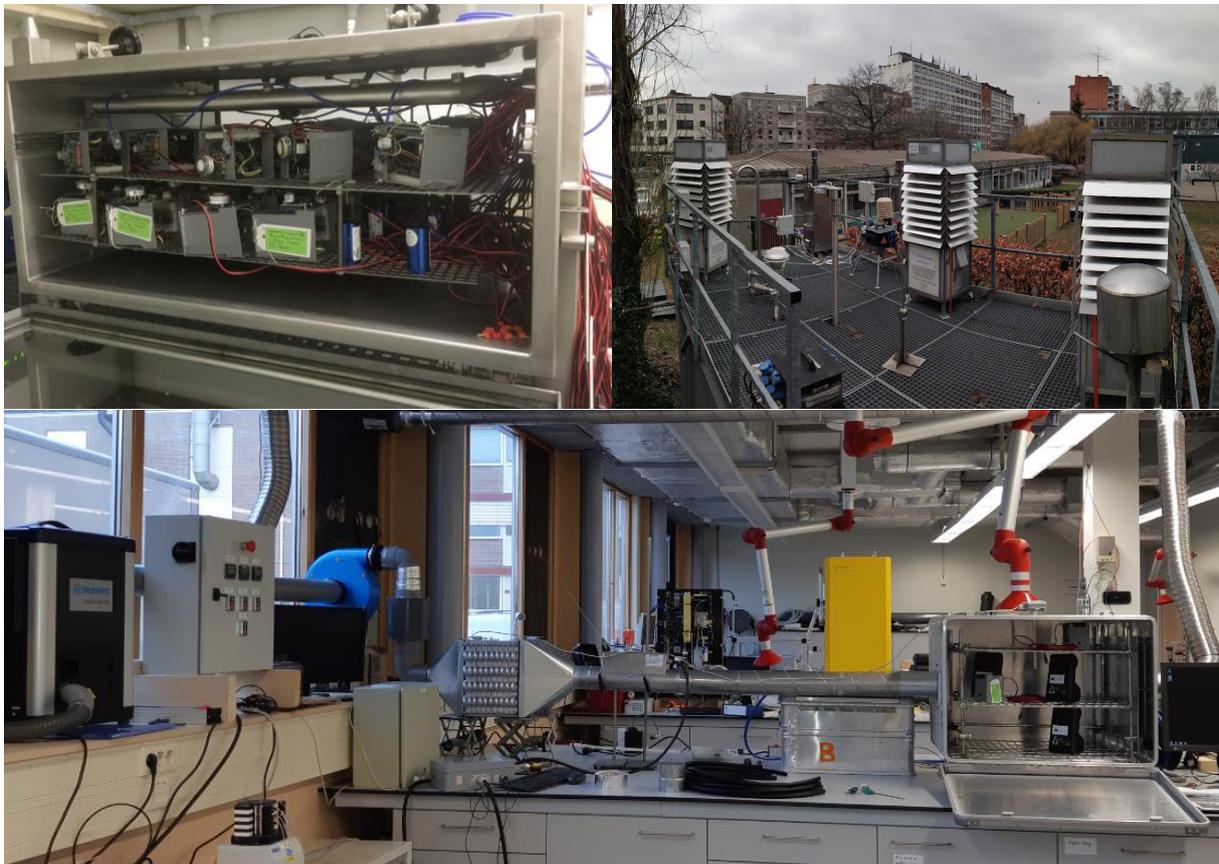


## Performance evaluation of low-cost air quality sensors in the laboratory and in the field

Set up and testing protocol of NO<sub>2</sub>, O<sub>3</sub> and PM sensors

Authors: Ernie Weijers, Jordy Vercauteren, Daniëlle van Dinther



## Introduction

This document describes the testing procedures of low- and medium-cost sensor systems for the monitoring of gaseous compounds and particulate matter (PM) in ambient air as carried out in the VAQUUMS project. The goal is the evaluation of the performances of sensors for regulatory (Air Quality Directive) as well as non-regulatory measurements (like in citizen science).

Low- and medium cost sensors are expected to significantly augment current monitoring capabilities for regulatory as well as non-regulatory purposes, provided they produce reliable data. Up to now there are, however, no formal guidelines by which these devices can be evaluated. Preliminary tests suggest that many of the commercially available air monitoring sensors have poor to modest reliability, do not perform well under ambient conditions, and do not always correlate well with data obtained using the “standard” measurement methods. In addition, poor quality data obtained from sensors may frustrate users and jeopardize the successful development of the “low-cost” sensor technology. Therefore, there is an obvious need to better characterize the actual performance of air monitoring sensors as well as to educate the public and users about both the potential and the limitations of these devices.

## 1 Laboratory and field testing

In order to provide the information about the performance of “low-cost” sensors, VAQUUMS carried out a characterization of available sensors using both field- and laboratory facilities. This report describes the procedures of the laboratory as well as the field testing.

Sensors first underwent the testing in the laboratory. Characterization chambers were used to challenge the sensors under various conditions of relative humidity (RH), temperature T, pollutant and interfering species. Concentrations in the test chambers were set out to be in the same order of magnitude as in typical ambient air. Influence of varying temperature and relative humidity as well as gaseous interference are studied in detail. Due to difficulties with the generation of PM test aerosol the maximum testing concentrations for PM ended up being higher than what is usually found in ambient air.

After the laboratory tests all sensors were brought to the air monitoring testing site at Borgerhout (Belgium) for field testing. Depending on the direction of the wind this site can be classified as either an urban traffic or an urban background location.

During the field tests at the Air Quality Monitoring Station (AQMS) sensors and official methods (reference monitors for gases and equivalent monitors for PM) are co-located and results compared. The data acquired will be influenced by prevailing ‘conditions’ such as the type of aerosol, concentration levels and interfering compounds, weather conditions (temperature, humidity, etc.). Therefore, results may vary with different meteorology and air composition (e.g. resulting in different sensor cross-sensitivities).

Basically, the sensor or sensor system is treated here as a black box (as it is delivered by the manufacturer). No effort has been made to evaluate the *internal* operational achievements or to perform any type of data compensation algorithm (apart from required calibrations for the gas sensors). Of each type of gas sensor unit five copies were tested. For PM-sensors 3 copies were used in the lab and two additional units were tested in the field to also bring the total number of field tested unit to 5.

For each sensor type, the results of the field and laboratory tests, as well as other observations are summarized in a dedicated document (factsheet). A final report will bring together the most important

conclusions regarding the testing a concise manner. All data collected, documentation and testing results will be made available at the VAQUUMS website ([www.vaquums.eu](http://www.vaquums.eu)).

## 2 Sensor unit assembly

Most sensors require some sort of hardware and software for practical operation. In our setup most sensors were assembled as sensor units consisting of:

- the sensor itself;
- a microcomputer (Arduino Uno) to read the sensor data;
- a wifi module (ESP8266) to send the data to a central database.

The central database consisted of 2 laptop computers (one main system and one back-up system). Raw sensor data were stored at 1-second resolution. Software for most of units was custom made, either based on the sensor info sheets or on code found online.

## 3 Gas sensors lab testing setup

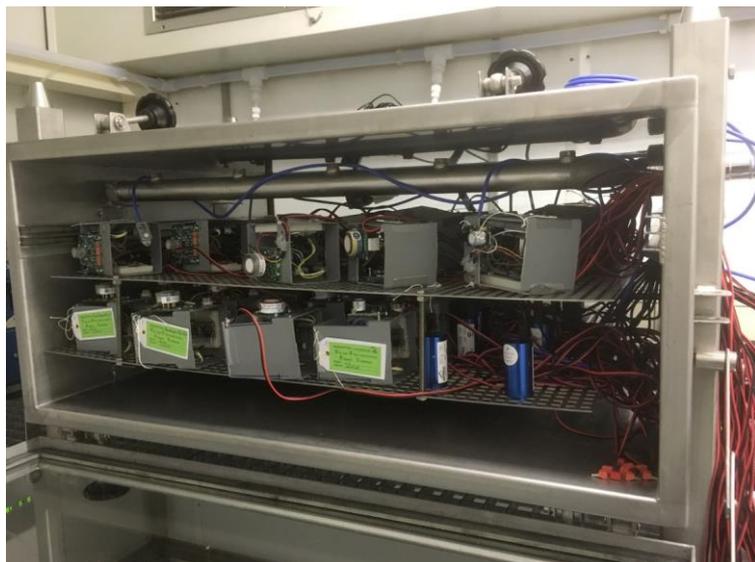
### Experimental methods

RIVM uses the MCZ model CGM as a dynamic system for generating, mixing and delivering a known concentration of a test gas in air. The system dilutes up to 6 gas mixtures in cylinders with filtered air. The filtered air has a sufficient level of purity to eliminate gaseous interference of both reference measurements and sensor values. A calibrated internal O<sub>3</sub> generator generates the requested O<sub>3</sub> concentrations. The system has 6 mass flow controllers of 0-100 ml/min for gas mixtures and one of 0-100 l/min for dilution of the mixtures with air.

The dilution system adds water by means of a liquid mass flow meter to achieve a desired humidity. The software of the system will compensate for the added volume of water.

### Exposure chamber

RIVM uses an exposure chamber (Figure 1) of sufficient capacity to accommodate several sensors simultaneously (inner dimensions 64x86x37 cm, DxWxH). The sensors are placed on a grid above the lower manifold, at 10 cm above it a second grid is available. The generated atmosphere passes through this chamber. The air enters the chamber through a manifold with ten nozzles situated at the top. The nozzles point upwards to the roof of the chamber. The air leaves the chamber through a similar manifold at the bottom of the chamber with ten nozzles pointing downwards. This configuration causes a downwards laminar flow in the chamber. The surfaces of the chamber and the grids are made of stainless steel with borosilicate windows in the doors.



*Figure 1 Exposure chamber including all gas sensors*

A reference method measures the concentration of the generated calibration gas mixture in the exposure chamber. The sample inlet of the reference method is positioned in the center of the chamber. Hence, if differences would exist between each sensor and the reference method, it is as little as possible. The exposure chamber is located in a temperature controlled climate room with an upwards laminar airflow. The room has automated temperature control. In this manner the temperature in the chamber is controlled indirectly. Due to the electronic components next to each sensor the temperature in the chamber is (slightly) higher and varies with the air flow through the chamber.

## Reference analyzers

The reference continuous gas analyzers (Figure 2) used to measure gas concentrations in the laboratory evaluation are:

- Thermo 49i UV photometric O<sub>3</sub> analyzer;
- Teledyne API Chemiluminescence Nitrogen Oxides Analyzer Model 200E.



*Figure 2: reference gas analyzers*

## 4 PM sensor lab testing setup

### Experimental methods

TNO used a PALAS RBG 100 system for generating a range of PM-concentrations in the test box. A powder (in this case ISO 12103-1, test dust made from Arizona desert sand dust) is filled into a cylinder. A feed piston is used to press the powder up in the cylinder while a dispersion brush on top of the cylinder brushes off the powder.

### Exposure chamber

TNO used an exposure chamber (Figure 3) of sufficient capacity to accommodate several sensors simultaneously (inner dimensions 57x75x55 cm, DxWxH). The sensors were placed on a grid 2.5 cm above the lower manifold, above this lower grid two grids are placed around 20 cm apart.



*Figure 3: Exposure box used for PM testing with the three grids visible*

An equivalent monitor, in this case a Palas Fidas 200, measures the concentration of the generated PM in the exposure chamber. The sample inlet of the reference method is positioned in the center of the chamber. In order to test the homogeneity of PM within the chamber tests were carried out switching the inlet in different spots in the chamber. The test showed that the PM was homogeneously distributed within the chamber. The inlet flow is controlled both in temperature and relative humidity in order to reach the desired conditions inside the chamber. Due to the electronic components next to each sensor the temperature in the chamber is higher and can vary with the air flow through the chamber. In order to limit the temperature effect from the sensors and ensure sufficient space in between the sensors the experiments were carried out in two batches.

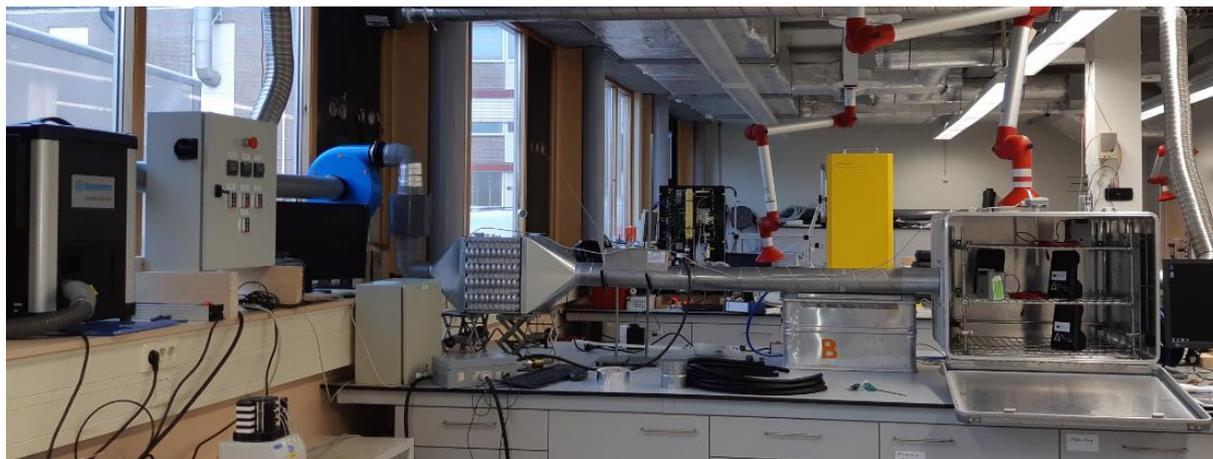


Figure 4 complete experimental setup for PM lab testing

## Reference analyzer

The equivalent PM analyser used to measure PM concentrations in the laboratory evaluation was a Palas Fidas 200 analyser (Figure 5). The Fidas 200 is an aerosol spectrometer developed specifically for regulatory air pollution control. It analyzes continuously the fine dust particles present in the ambient air in the size range 180 nm – 18 µm and calculates simultaneously the immission values PM<sub>10</sub> and PM<sub>2.5</sub> to be monitored by law. At the same time PM<sub>1</sub>, PM<sub>4</sub>, PM<sub>total</sub> (up to 18 µm), the particle number concentration Cn, and the particle size distribution are calculated and recorded.



Figure 5: Palas Fidas 200 reference analyser

The Fidas 200 utilizes the acknowledged principle of single particle light scattering size analysis and is equipped with an LED light source of high intensity ( $dp_{min} = 180 \text{ nm}$ ). The sampling system of the Fidas 200 operates with a volume flow of approximately  $0.3 \text{ m}^3/\text{h}$

The actual aerosol sensor is an optical aerosol spectrometer which determines the particle size using Lorenz-Mie scattered light analysis of single particles. The particles travel individually through an optically confined measurement volume which is homogeneously illuminated with polychromatic light. Every particle generates a scattered light impulse that is detected at an angle between  $85^\circ$  and  $95^\circ$ . The particle number is determined based on the number of scattered light impulses. Particle size is derived from the level of a scattered light impulse.

Precise optics, high light output from the polychromatic LED used, and powerful signal processing electronics using logarithmic A/D conversion allow detection of particles down to 180 nm diameter.

The detection of small particles, which can be found in high concentration in particular close to roads, is of importance, e.g., for the correct determination of PM<sub>2.5</sub>.

## 5 Sensor evaluation criteria

### Introduction

The “characterization chamber” was used to challenge the sensors with changing concentrations of gases/PM under controlled temperature (T) and relative humidity (RH) levels. The evaluation is based on a comparison between the sensor device and reference instruments measuring the same pollutant(s). For PM we focused on PM<sub>2.5</sub> and PM<sub>10</sub>. The sensor systems were evaluated in a group of three to five identical devices to provide sufficient statistical information about the comparability with reference instruments. Typical parameters (e.g., AQ-SPEC, 2016; Spinelle,2013) possibly affecting actual air quality measurements in the field tested in the experiment are:

- Accuracy;
- linear correlation with a reference monitor;
- stability of the sensor signal during steady-state condition (gas sensors only);
- co-pollutant interference;
- Temperature (T) and Relative Humidity (RH) ;
- between-sensor uncertainty.

The experiment consists of two parts: 1. a concentration ramping part where the pollutant level subsequently increases and decreases, and 2. a steady-state part where the pollutant concentration remains stable while varying temperature and relative humidity. The accuracy and linear correlation coefficient were evaluated based on data acquired from the ramping stage. For the gas sensors the ramping part was used to calculate a calibration equation ( $y=ax+b$ ) per individual sensor by comparing the sensor data with the reference data. These individual calibrations were applied to the gas sensor data for all the further evaluations.

For PM it was not possible to reach a steady state conditions with stable concentrations. Thus the PM concentrations variate while keeping the temperature and relative humidity stable. In order to test the linearity mean 10 minute values of the sensors are compared to the reference.

### Definitions

#### Accuracy

Accuracy A is defined as:

$$A (\%) = 100 - \frac{|\bar{X} - \bar{R}|}{\bar{R}} * 100$$

with  $\bar{X}$  is the average concentrations measured by all the sensors and  $\bar{R}$  the average concentration of the reference instrument during the steady-state period (Polidori, 2016). In the chamber tests, accuracy is derived from the concentration ramping experiment at 15 °C and 75% RH. After each step of the ramping phase, the difference between the average of the sensors and the reference instrument is calculated. The higher the (positive) value (percentage) of A, the higher the sensor’s accuracy. A value of 100% implies that sensors measure exactly what the reference instrument measures.

## Correlation with the reference monitor

The linearity between the average measurement data derived from the sensors and the corresponding reference instrument is given by the correlation coefficient ( $R^2$ ). The associated regression line is calculated (with slope and intercept value).

## Stability of the sensor signal during steady-state condition (gas sensors only)

This parameter gives an idea of the stability of a sensor signal under steady-state conditions. The better the stability of a sensor, the lower the 'noise' of the signal will be.

The sensor's *stability* is expressed as SD and RSD%

- SD = standard deviation of the 1-min averages during steady state condition
- RSD% = relative standard deviation =  $(SD / \bar{X} \text{ during steady state}) \times 100$

The sensor stability is calculated for all individual sensor units.

During the gas sensor testing experiment, the steady-state time period is roughly 2 hour and since 1-min measurements are collected, some 120 measurement data points are used for this analysis. This parameter is calculated for various combinations of pollutant concentrations, temperatures and relative humidities.

For the PM sensor testing, due to the fact that PM concentrations are not constant, it was not possible to determine this parameter.

## Cross sensitivity (gas sensors only)

Gas sensors normally suffer from cross-sensitivity (either positive or negative) to other gaseous species. In the laboratory, the effect of gaseous interferences is evaluated by exposing a sensor to a concentration of the pure interferent.

## Influence of Temperature (T) and Relative Humidity (RH)

External parameters like temperature and relative humidity might influence the sensor's ability to correctly measure the pollutant concentrations. In the laboratory, gas sensors are tested under preset temperature and relative humidity conditions: 5°C, 15°C and 30°C, 45%, 75% and 90%, respectively. For PM sensors the temperature and RH-values are tested under the following conditions: 15°C, 25°C and 35°C, and 20%, 50% and 80% respectively. In practice temperatures sometimes deviated a bit from the set values due to the heat generated by the sensor units themselves.

## Between- sensor uncertainty

The between-sensor uncertainty gives an idea of the difference between different units of the same type of sensor. The lower the in-between sensor uncertainty the higher the comparability of different units of the same type of sensor. The in-between sensor uncertainty is calculated as follows:

$$u(bs, s) = \left( \frac{\sum_{i=1}^n \sum_{j=1}^p (y_{ij} - \bar{y}_m)^2}{n(p-1)} \right)^{\frac{1}{2}}$$

where

$y_{i,1}, y_{i,2}$  and  $y_{i,j}$  are the sensor measurements for period  $i$ ;

$\bar{y}_m$  mean result for period  $i$ ;

$n$  is the numbers of measurement over time.

$P$  number of replicates for period  $i$ .

For the gas sensors this uncertainty is derived from 5-min averages over the entire experiment.

For PM-sensor the uncertainty is calculated based on the 10-min averages of the concentration ramping part of the experiment.

## 6 Laboratory testing procedure for gas sensors

### Preparation

The reference instruments, as described earlier, were outside the climate room (because of optimal performance) and the sample tube is insulated (outside the climate room). Six Papago TH 2DI DO ETH sensors (Figure 6) were used for measuring temperature and relative humidity, one outside the chamber to measure inside the climate room (the surroundings of the exposure chamber) and five spread inside the chamber. Inlets of the NO<sub>2</sub> sensors were facing upwards and were equally spread over the grid. Due to the available space, the O<sub>3</sub> sensor inlets were facing sideways. Regarding the laminar flow as described earlier, the sensors and gas instruments sample from the same flow inside the chamber.

Each gaseous sensor had its own power cord(s) (Figure 7). Sensors were switched on at least an hour before the test (and the data logging) began. Data was sent using Wi-Fi and collected on a laptop or downloaded (for the Envea CairPol sensors) offline after the end of the experiment.

The testing of the sensors was carried out in two sessions. In the first session, with NO<sub>2</sub>, six series of five identical gaseous sensors (i.e. same make and model) were installed on the grid on top of the lower manifold. During the second session, with O<sub>3</sub>, the extra grid was placed on top of the lower one, additionally holding four series of five identical sensors (except for the Envea CairPol NO<sub>2</sub>: four). This session consisted of an extra test at the end, using both gases: NO<sub>2</sub> and O<sub>3</sub>.

### Standard procedure

The goal here was to evaluate the sensor performance in different concentration ranges at various temperatures and relative humidities.

The testing procedure needed 34 steps per gas component. The order of steps is given in Table 1 and visualized in Figure 9. In essence, the designed procedure consists of three experimental modes: effect of T and RH, concentration ramping and effect of interferent gases.



Figure 6 Papago T-%rh measuring module



Figure 7 Impression of the power supply

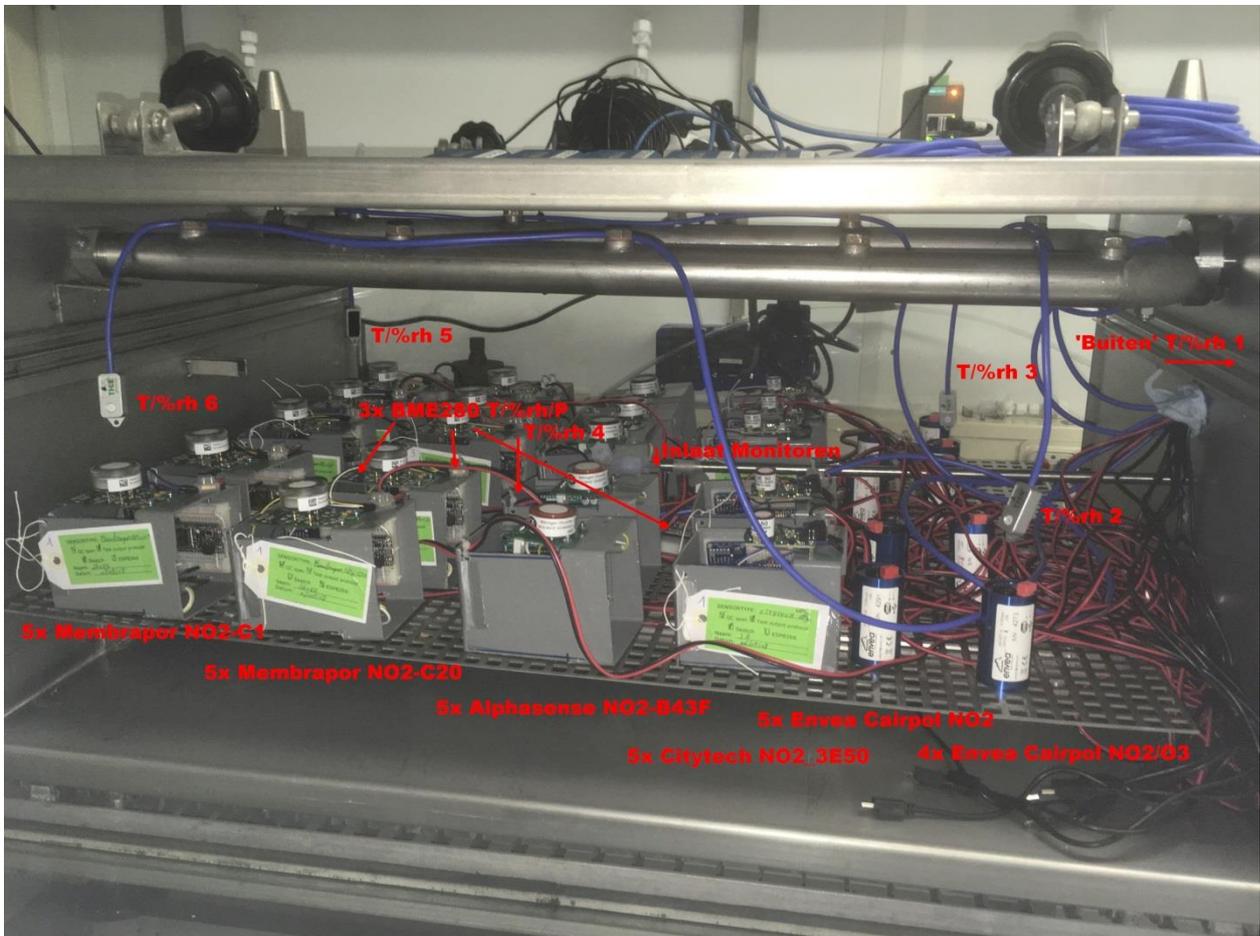


Figure 8 The arrangement of the sensors in the first test ("Buiten" means "Outside" and "Inlaat Monitoren" "Inlet Monitors")

Table 1 Temperature, humidity and concentration setpoints during the tests

Step nr	Duur (hh:mm)	Temperature (°C)	Humidity (%RH)	NO2 Concentration (ppb)	NO2 Concentration (µg/m <sup>3</sup> )	O3 Concentration (ppb)	O3 Concentration (µg/m <sup>3</sup> )
1	4:00	5	45	20	38	30	60
2	2:00	5	45	50	96	60	120
3	2:00	5	45	80	153	90	180
4	2:00	5	75	80	153	90	180
5	2:00	5	75	50	96	60	120
6	2:00	5	75	20	38	30	60
7	2:00	5	90	20	38	30	60
8	2:00	5	90	50	96	60	120
9	2:00	5	90	80	153	90	180
10	6:00	15	45	80	153	90	180
11	2:00	15	45	50	96	60	120
12	2:00	15	45	20	38	30	60
13	2:00	15	75	20	38	30	60
14	2:00	15	75	50	96	60	120
15	2:00	15	75	100	191	110	220
16	2:00	15	75	150	287	160	320
17	2:00	15	75	120	230	130	260
18	2:00	15	75	60	115	70	140
19	2:00	15	75	0	0	0	0
20	2:00	15	75	40	77	50	100
21	2:00	15	75	80	153	90	180
22	2:00	15	90	80	153	90	180
23	2:00	15	90	50	96	60	120
24	2:00	15	90	20	38	30	60
25	1:00	30	90	20	38	30	60
26	6:00	30	45	20	38	30	60
27	2:00	30	45	50	96	60	120
28	2:00	30	45	80	153	90	180
29	2:00	30	75	80	153	90	180
30	2:00	30	75	50	96	60	120
31	2:00	30	75	20	38	30	60
32	2:00	30	90	20	38	30	60
33	2:00	30	90	50	96	60	120
34	2:00	30	90	80	153	90	180

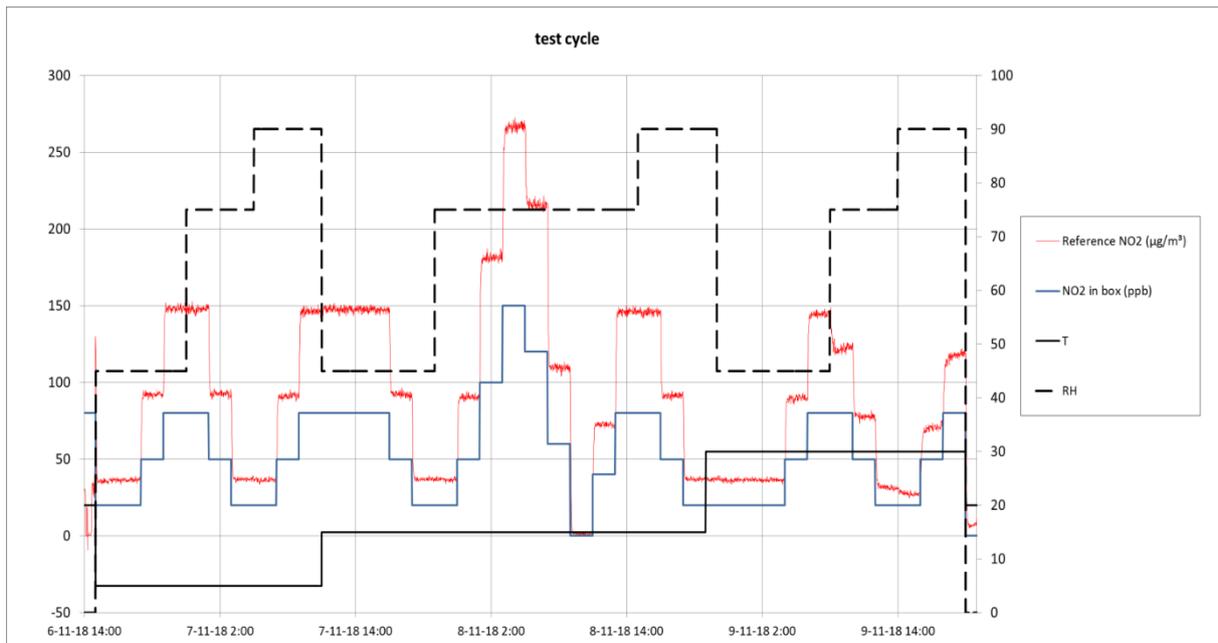


Figure 9: Overview of NO<sub>2</sub>, T and RH for the gas test protocol

Explanation:

Step 1 – 9:

Temperature fixed at 5°C;

Relative humidities subsequently fixed at 45, 75, 90%;

At each fixed humidity level varying concentrations (low, medium, high) of NO<sub>2</sub> (or O<sub>3</sub>) in increasing, in decreasing and again in increasing order.

Step 10 – 24:

Temperature fixed at 15°C;

Relative humidities subsequently fixed at 45, 75, 90%;

At each fixed humidity level varying concentrations (low, medium, high) of NO<sub>2</sub> (or O<sub>3</sub>) in increasing, in decreasing and again in increasing order (“concentration ramping experiment”)

For the determination of linearity and correlation coefficients additional concentration setpoints have been added here.

Step 26 – 34:

Temperature fixed at 30°C;

Relative humidities subsequently fixed at 45, 75, 90%;

At each fixed humidity level varying concentrations (low, medium, high) of NO<sub>2</sub> (or O<sub>3</sub>) in increasing, in decreasing and again in increasing in order.

Once the chamber had reached the desired average ambient conditions the concentration ramping experiment began (step 13– 21). A stabilization period was needed (15 min) after each concentration step. In total, concentration steps were selected to simulate a diverse pollutant profile from low to high (very high) and from high to low.

Effect of T and RH

The temperature and relative humidity parameters vary each at a low, medium and high level; in total there are 9 different combinations (at a fixed concentration level). The following table shows the experimental set points for both T and RH:

Table 2: temperature and relative humidity settings

	T	RH
	°C	%
<b>low</b>	5	45
<b>medium</b>	15	75
<b>high</b>	35	90

### Effect of interferent gases

In the laboratory, the effect cross interference was evaluated by exposing a sensor to a target concentration of pure interferents. These were chosen from information provided in previous studies in the literature. In our case, with respect to NO<sub>2</sub>, the interferent was O<sub>3</sub>, and vice versa.

## 7 Laboratory testing procedure for PM sensors

### Preparation

The reference instrument, as described earlier, was outside the climate room (because of size and optimal performance of the instrument) and the sample tube was insulated (outside the climate room). Three LabJack EI1034 were placed inside the exposure box (one on each grid) to measure the temperature inside the box. Furthermore an EE210 E + E elektronik measured the temperature and humidity in the center of the box. All PM sensors were placed as described by the manufacturer in order to ensure that air flow through the sensor was possible.

Each PM sensor had its own power cord(s). Sensors were switched on at least an hour before the test (and the data logging) began. Data was send using Wi-Fi and collected on two laptops. When a PM sensor was malfunctioning the power supply (which were labelled) was unplugged to try and retrieve the signal.

The testing of the sensors was done in two sessions. In the first session the three identical PM sensors (i.e. same make and model) of Nova fitness (SDS011), Shinyei (both PPD42 and PPD60), Honeywell (HPMA) and Dylos (1700) were tested. During the second session the three PM sensors of Plantower (PMS7003), Winsen (SH03A), and Alphasense (OPC-N2) were tested.

### Standard procedure

The goal here was to evaluate the sensor performance in different concentration ranges at various temperatures and relative humidities. Results from these experiments will confirm performance parameters such as accuracy and linear correlation as defined above. For the testing of the PM sensors the T and RH had to be set manually therefore the duration of each setting is not constant.

The testing procedure needed 28 steps. The order of steps is given in Table 3, Table 4, Figure 10 and Figure 11.

Table 3: Temperature, humidity and average concentration during the steps for batch 1

Step	Duration	T	RH	PM <sub>1</sub>	PM <sub>2.5</sub>	PM <sub>4</sub>	PM <sub>10</sub>	PM <sub>total</sub>
nr	(hh:mm)	(°C)	(%)	(µg m <sup>-3</sup> )				
1	14:20	30	20	8	38	113	307	497
2	2:35	30	50	18	86	263	751	1266
3	1:45	35	80	18	88	268	781	1297
4	14:10	30	20	0	0	0	0	0
5	19:40	25	20	9	46	153	510	954
6	15:50	35	20	18	88	260	726	1092
7	2:00	35	80	28	136	385	1016	1447
8	1:50	35	50	26	123	348	907	1265
9	1:50	25	50	27	129	369	975	1405
10	2:00	15	50	7	38	129	398	646
11	5:30	15	20	16	77	230	632	955
12	1:50	15	50	26	133	409	1212	1955

Table 4: Temperature, humidity and average concentration during the steps for batch 2

Step	Duration	T	RH	PM <sub>1</sub>	PM <sub>2.5</sub>	PM <sub>4</sub>	PM <sub>10</sub>	PM <sub>total</sub>
nr	(hh:mm)	(°C)	(%)	(µg m <sup>-3</sup> )				
1	18:50	15	30	0	0	0	0	1
2	2:25	15	50	26	156	552	1815	3060
3	1:00	15	80	31	166	561	1817	3036
4	14:15	15	20	24	126	403	1267	2109
5	9:09	15	20	1	4	16	61	105
6	2:15	15	80	5	32	118	401	653
7	1:50	15	50	3	19	67	206	323
8	2:10	15	20	16	84	273	846	1364
9	15:30	25	20	23	119	388	1248	2109
10	1:50	25	50	30	163	532	1649	2693
11	2:10	35	80	28	147	484	1556	2592
12	2:50	35	50	24	126	414	1345	2242
13	13:00	35	20	25	132	440	1462	2523
14	15:50	15	20	15	83	292	1025	1858
15	2:00	15	50	16	87	303	1063	1963
16	3:40	15	80	8	42	146	512	920

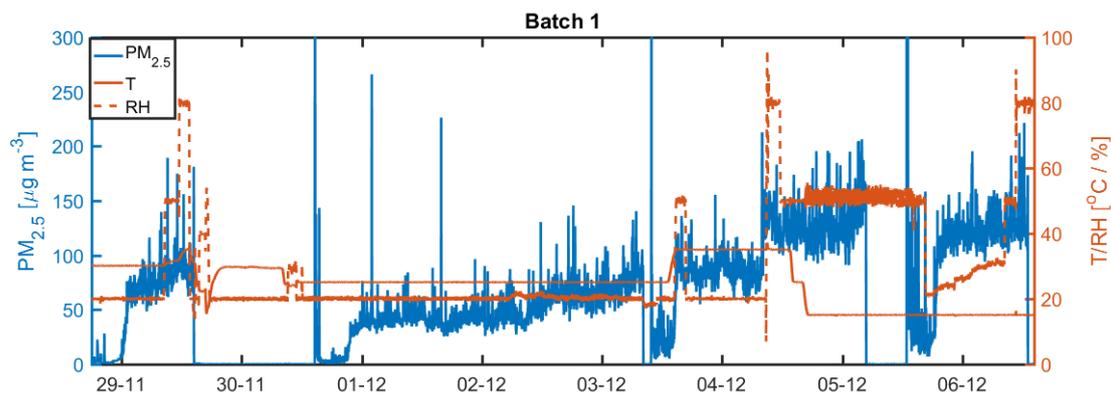


Figure 10: Overview of PM<sub>2.5</sub>, T and RH for the test protocol of batch 1

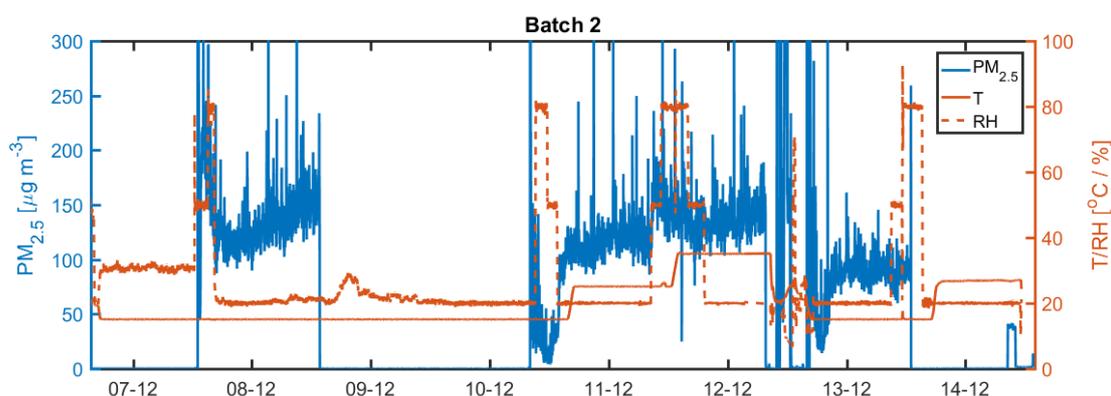


Figure 11: Overview of PM<sub>2.5</sub>, T and RH for the test protocol of batch 2

For both batches the sensors were tested when there was no PM present in the room. For batch 1 this occurred in step number 4 and for batch 2 in step number 1. For the other steps the PM concentrations varied by itself as a consequence of the generation of PM. Table 3 and Table 4 give the PM concentrations measured by the Fidas for different steps. The RH was fixed at 20%, 50% and 80%. For PM it was decided to have lower RH values than for O<sub>3</sub> and NO<sub>2</sub> since some PM sensors have problems with very low PM concentrations. Due to the heat production by the sensors itself it was not possible to fix the box at a very low temperature. Therefore the lowest temperature that was fixed was 15°C. Other temperatures at which the box was fixed during the steps were 25, 30 and 35°C. For batch 1 also some test were undertaken with a fixed temperature of 30°C. However, since this was reasonably close to 25°C it was decided to set the maximum fixed temperature to 35°C.

### Concentration range

The generated PM<sub>2.5</sub> concentrations ranged from a few µg/m<sup>3</sup> to 150 µg/m<sup>3</sup>. These levels represent a typical range of hourly PM-concentrations in Europe. The generated PM<sub>10</sub> concentrations ranged from a few µg/m<sup>3</sup> to 1500 µg/m<sup>3</sup>. The upper limit is higher than the typical upper range of hourly PM-concentrations in Europe.

### Particle size

In Table 3 and Table 4 the average PM<sub>1</sub>, PM<sub>2.5</sub>, PM<sub>4</sub>, PM<sub>10</sub> and PM<sub>total</sub> measured by the Fidas in the different steps for batch 1 and 2 are mentioned. The distribution along these PM sizes is more or less constant along the experiment. About 1% of the total PM concentration is caused by particle sizes below 1 µm. Around 4% by particles in between size 1 and 2.5 µm. Particles in between size 2.5 and 4 µm contribute to about 13% of PM<sub>total</sub>. And particles in between 4 and 10 µm, as well as those above 10 µm, contribute each about 41% to the PM<sub>total</sub> signal.

This size distribution is significantly different from typical ambient aerosol (with has relatively much more PM<sub>1</sub> and PM<sub>2.5</sub>). Since we assume that most cheap PM-sensor are internally calibrated in some sort of way based on ‘average ambient aerosol’ this coarser particle distribution can have a significant effect on certain test parameters. However it does allow us to have a better understanding of the true capability of these cheap PM sensor to actually measure coarser PM (between 2.5 and 10 µm).

## Effect of T and RH

The temperature and relative humidity parameters vary between a low, medium and high level; in total there are 9 different combinations (at a fixed concentration level). Table 5 shows the set points for both T and RH:

*Table 5: 3 levels of T and RH during the PM experiment*

	T	RH
	°C	%
<b>low</b>	15	20
<b>medium</b>	25	50
<b>high</b>	35	80

## 8 Field testing for gas and PM sensors

### Introduction

During the field tests at Air Quality Monitoring Stations (AQMS) sensors and reference methods of measurements were co-located and compared. The location of the test site was chosen because it typically covers a wide range in pollutant levels and composition. The site (Plantin en Moretuslei in Borgerhout, Antwerp) was chosen because the official VMM measurement station there was located 30m from one of the busiest roads in the city of Antwerp, Belgium. When wind blows from the directions of the road this site can be classified as an urban traffic station, when the wind blows from other directions it behaves as an urban background location.

Despite the wide range in concentration levels, one should still take into account that the results of the field tests are influenced by the ‘conditions’ during the test (such as the type of aerosol, concentration levels and interfering compounds, weather conditions,...) Results may be different under other conditions with different meteorology and air composition (e.g. resulting in different sensor cross-sensitivities). To highlight the effect of different conditions during the field evaluation we will take a closer look at some dedicated cases (= set of days with distinct conditions and /or concentrations/composition of pollutant).

### Shelter setup

Three shelters were especially designed and made for the field tests of the LIFE VAQUUMS-project. These shelters make sure that no rain or direct sunlight can reach the sensors. However, the design also ensures sufficient air circulation, such that the air inside the shelter is as similar as possible as the air outside the shelter. To do so we opted to place the sensors on grids and added two ventilators to each shelter to force the air from outside the shelters to flow over the sensors.

Each shelter (Figure 12) has a cabinet of 50 x 50 x 60 cm at the bottom, which is used to store the distribution plugs and power supplies. The top and the side of each cabinet include a fan of 12 cm diameter, to ensure air circulation. Above the cabinet there is an semi-open framework of 50 x 50 x 80 cm. within this framework, five grid boards were placed to store the sensors. The four sides of the

framework are closed with nine aluminum lamina at a 45° angle to avoid rain to come in and to ensure sufficient ventilation. The three shelters were placed on the roof of the reference station about five meters above ground level and less than 3m from the inlet of the official monitors (Figure 13).



*Figure 12: shelter with some sensor units inside*

Within each shelter eight sensors can be placed on each grid board. The five sensors of each type are spread out over various shelters and levels. Each shelter contains one or two sensors of each type. They are placed on different levels in the three shelters (i.e. the 5 sensors of each type are placed on the lowest, 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup> and highest grid board when viewed over the three shelters). Only the Dylos is an exception on this. Since this sensor is higher, it only fits one grid board per shelter. They are therefore placed on the lowest, 3<sup>rd</sup> and highest grid board, with two shelters containing two Dylos sensors on the same grid board. Finally, all wind directions (N, E, S, W) are faced at least by one sensor of each type.



Figure 13: 3 shelters on the roof of the monitoring station in Borgerhout, Antwerp.

## Reference monitors

The monitoring station was equipped with the following reference monitors:

- Teledyne API T400 UV Absorption O<sub>3</sub> analyzer
- Thermo 42i Chemiluminescence NO-NO<sub>2</sub>-NO<sub>x</sub> Analyzer
- PM: Palas Fidas 200 (=equivalent to the gravimetric reference)

## Evaluation

The sensors shall be tested in a way that is representative of its practical use; practical frequencies of calibrations and checks shall be applied in the different trials if required by the manufacturer. In the field test 5 sensors of the same type (model, hardware, firmware and software configuration and version) are tested for:

1. between-sensor uncertainty (see lab test for calculation formula) at 5min, 60min and 24h.
2. comparability with the EU reference method (24h average) > uncertainty at limit value<sup>a</sup>, R<sup>2</sup>
3. comparison with reference/equivalent monitor at 5 min, 60 min and 24h averaging time (timeplot, scatterplot with fit and R<sup>2</sup>).
4. drift will be assessed by comparing ratio (or absolute difference) between sensor and reference in function of time.

<sup>a</sup> The calculation of the uncertainty at the limit value is done with an Excel spreadsheet based on the 'Guidance for the Demonstration of Equivalence of Ambient Air Monitoring Methods'. <http://ec.europa.eu/environment/air/quality/legislation/pdf/equivalence.pdf>



## References

Polidori, A., Papapostolou, Sc.D., Zhang, H., 2016: Laboratory Evaluation of Low-Cost Air Quality Sensors – Laboratory Setup and testing Protocol, AQ-SPEC.

Spinelle L., Aleixandre M. and Gerboles M. 2013. Protocol of evaluation and calibration of low-cost gas sensors for the monitoring of air pollution. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Report EUR 26112 EN.

## Disclaimer

The laboratory evaluation was conducted with simulated pollutant and interferent concentrations that were generated. Generated environments may not be able to fully replicate the conditions that may be experienced under ambient settings. The sensor assembly, installation, and use can also impact the reliability. VAQUUMS makes no claim, warranty, or guarantee that these devices will or will not work when operated by other users for their specific applications.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.