Validation of SPS30 and Piera sensors – City Probe 2

Report 968765

TEKNOLOGISK INSTITUT

Title:
Validation of SPS30 and Piera sensors – City Probe 2

Prepared for:
Montem A/S
Att: Christian Østergaard Laursen
Karen Blixens Boulevard 7
8220 Brabrand

Written by:
Teknologisk Institut
Teknologiparken
Kongsvang Allé 29
8000 Aarhus C

April 29 2021

Authors:
Thor-Bjørn Ottosen, Ph.D, specialist, e-mail: thot@teknologisk.dk, tlf.: 7220 1432
Stig Koust Hansen, Ph.D, consultant, e-mail: stko@teknologisk.dk, tlf: 7220 1151

Quality control:
Quynh T. Nguyen, Ph.D, consultant, e-mail: thng@teknologisk.dk , tlf.: 7220 1254

Table of Contents

1. Summary of assignment

MONTEM A/S has requested the Danish Technological Institute to test the accuracy of three Sensirion SPS30 (the sensor currently contained in CityProbe 2) and three Piera 7100 sensors against reference equipment under controlled conditions.

2. Summary of results

The results showed a generally good linear correlation between measurements by the Sensirion and Piera low-cost sensors and by the reference instruments for different size fractions (coefficient of determination R^2 mostly above 0.8), though the sensors systematically underestimated the concentrations. One sensor (City Probe 49) underperformed, while sensor-to-sensor variation was substantial.

3. Protocol and analytical method

3.1. Experimental setup

In the experiments, a 3 % potassium chloride (KCl) solution was used as a source of atmospheric particles. Particles were generated using a particle generator (PALAS GmbH AGK 2000). The experiments were carried out in a test chamber with a volume of 20 m^3. The walls of the test chamber are covered by Teflon foil to reduce the adsorption of particles. The test chamber is air-tight and non-ventilated and is therefore suitable for testing the performance of low-cost sensors. An external ventilator set on lowest fan speed was used to circulate the air in the test chamber during the experiments to ensure homogeneous mixing. Two experiments were performed, one with the TEOM measuring $PM_{2.5}$, referred to as *Experiment 1*, and one with the TEOM measuring PM_{10}, referred to as *Experiment 2*. The MONTEM sensors were placed inside the test chamber and were continuously monitoring the particulate matter (PM) concentrations. The MONTEM sensors were named CityProbe-47 to CityProbe-52, with CityProbe 47-49 being Piera sensors and CityProbe-50-52 being Sensirion sensors. CityProbe-48 was not operational during the first experiment, which is why these data are missing from the analysis. The reference instruments are placed outside the test chamber with sample probes placed in the vicinity of the MONTEM sensors.

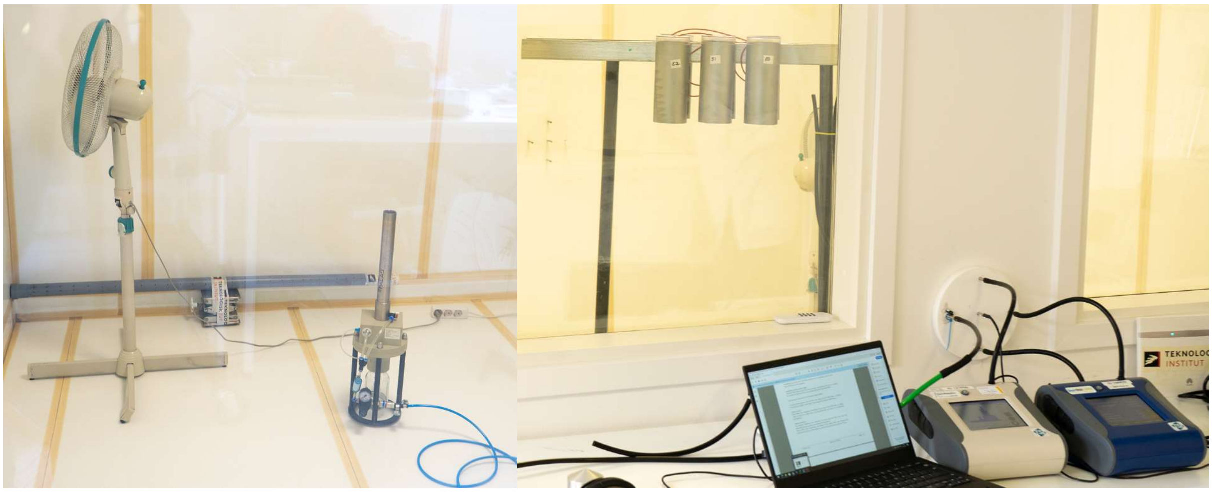


Figure 1. Experimental setup inside the test chamber, with the PALAS particle generator placed on the floor with particles being vertically-emitted into the chamber (left). The sensors, DustTrak and OPS are visible (right) while the TEOM is not visible in the figure.

3.2. Analytical method

The particle mass was measured with an Optical Particle Sizer (OPS, TSI 3330) as well as a TEOM (1405 TEOM™ Continuous Ambient Particulate Monitor, Thermo Scienfitic). The OPS measures the particle size distribution in five different size bins (0.3 µm -- 0.5 µm; 0.5 µm -- 1.0 µm; 1.0 µm -- 2.5 µm; 2.5 µm -- 5.0 µm; 5.0 µm -- 10 µm). The five mass fractions ($PM_{0.5}$, PM_1, $PM_{2.5}$, PM_5 and PM_{10}) are then calculated based on spherical particles with density equal to 1. The TEOM directly measures the mass of the particulate matter; however it is not able to measure multiple PM fractions simultaneously. Hence, PM fraction ($PM_{2.5}$ and PM_{10}) are measured during two separate experiments. The TEOM is generally considered to be the state-of-the art instrument for continuous real-time measurement of particulate matter. A DustTrak instrument (TSI DustTrak DRX model 8533), which measures particle mass in the size range ~0,1-15 µm and mass concentration range 0.001–150 mg/m^3 was also used. The instrument measures the size fractions PM_1, $PM_{2.5}$, PM_4, PM_{10} og PM_{total} with a time resolution of 10 seconds. The measurement principle is optical and based on laser diffraction. Since the TEOM is a better reference instrument compared to DustTrak, while the OPS size bins were set to better match the measurement intervals by the sensors than the DustTrak, the DustTrak data was only used for purpose of comparing among laboratory-based reference instrument (TEOM) and mobile instruments (OPS and DustTrak).

3.3. Data analysis

The mass fraction of the individual size bin from the OPS was used as a measure of the particle size distribution. This was subsequently multiplied with the corresponding mass fraction from the TEOM. In this way, respectively $PM_{2.5}$ and PM_{10} was measured with the TEOM to a high accuracy, and an estimate of the particle size distribution was calculated from the OPS measurements.

4. Results

4.1. Time series

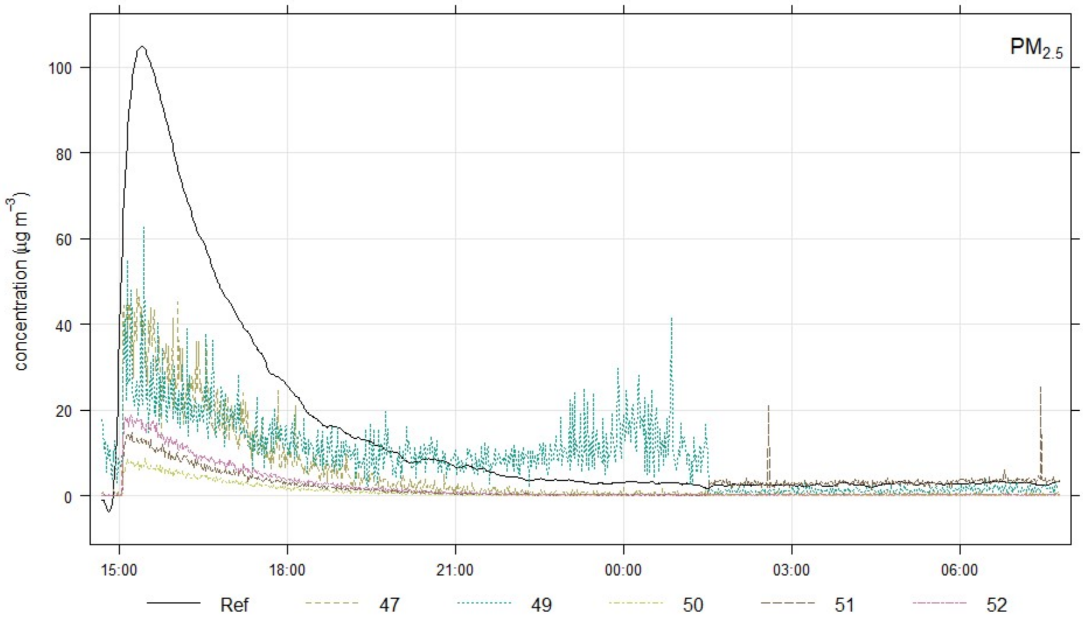


Figure 2. Time series of Experiment 1 with $PM_{2.5}$ TEOM as reference

An example of the results obtained from the first experiment for $PM_{2.5}$ is shown in **Figure 2**. *Ref* refers to the reference instrument, in this case the TEOM, and the numbers refer to the numbers of the CityProbes. It is evident that all the low-cost sensors systematically underestimate the concentrations, especially for the high concentrations. It is likewise evident that the Piera sensors (47, 48 and 49) are better at capturing the high concentrations with the drawback that the data become more noisy. Moreover, there is a substantial difference between the sensors of the same producer and model, which means that individual calibration of each sensor is required for precise measurements. In addition, the figure shows instrumental artefacts for CityProbe 49, of which concentrations decreased much later than the reference measurements and the other low-cost sensors. Similarly, CityProbe 51 showed two spikes in the end of the time series, which is likewise attributed to experimental artefacts. By comparing the figures for the various size fractions, it is evident that the bias (systematic measurement error) is largest for the larger particles and smaller for the smaller particles. The same patterns are evident for PM_{10} as seen below in **Figure 3**.

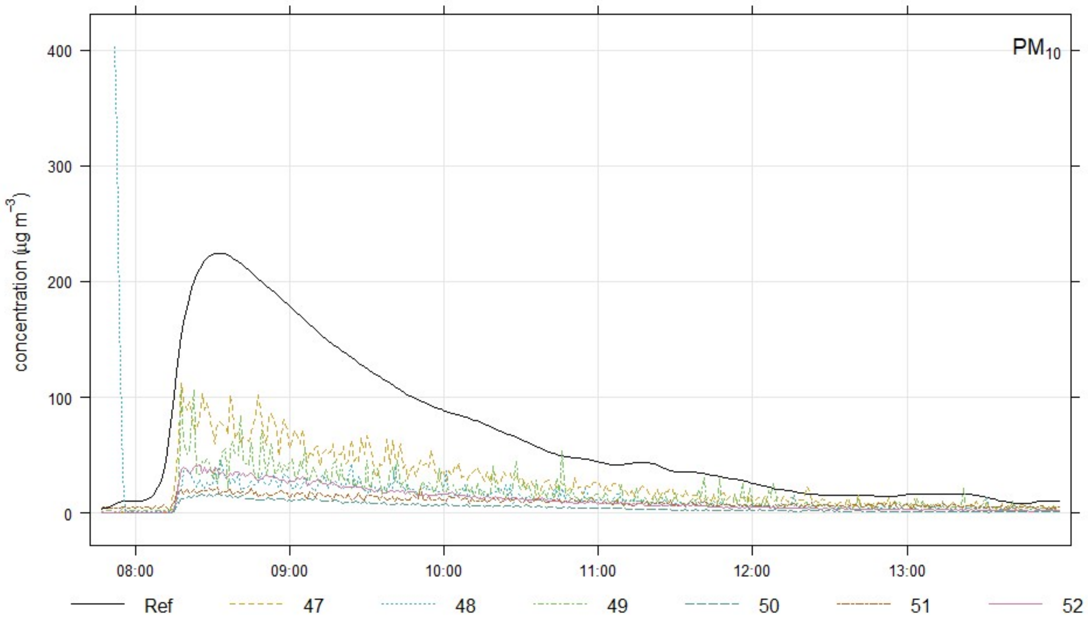


Figure 3. Time series of Experiment 1 with PM_{10} TEOM as reference

At the same time, it should be noted that different instruments employ different measurement principles and therefore could also differ from each other. Appendix 1 - *Comparison of reference data* shows a comparison of $PM_{2.5}$ and PM_{10} measurements measured by the standard reference instrument TEOM and more mobile reference instruments DustTrak and OPS.

4.2. Correlation

An example of a scatterplot for the low-cost sensors against the reference instruments is shown in **Figure 4**. Similar to the results from time series figures, it is again evident that all low-cost sensors systematically underestimate the concentrations, more so for the Sensirion sensors (CityProbe 50-52) than the Piera sensors (CityProbe 47-49). It is likewise evident that the Piera sensors are more influenced by noise and instrumental artefacts than the Sensirion sensors. All sensors show good linearity in the concentration span covered in the present test.

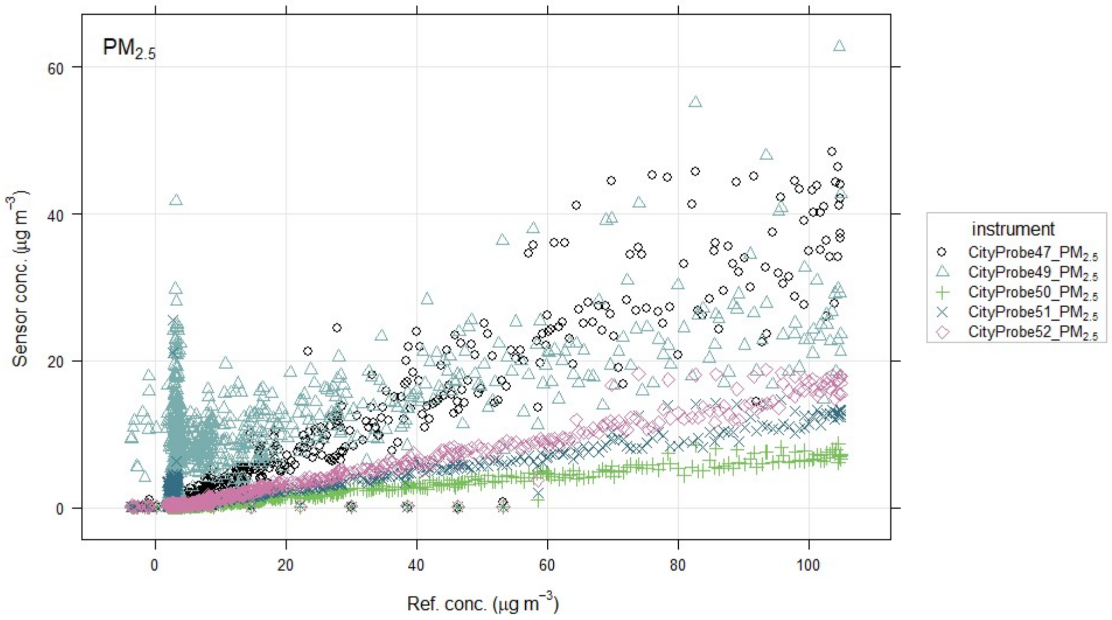


Figure 4. Correlation between concentrations measured by the sensors versus reference concentration (TEOM $PM_{2.5}$)

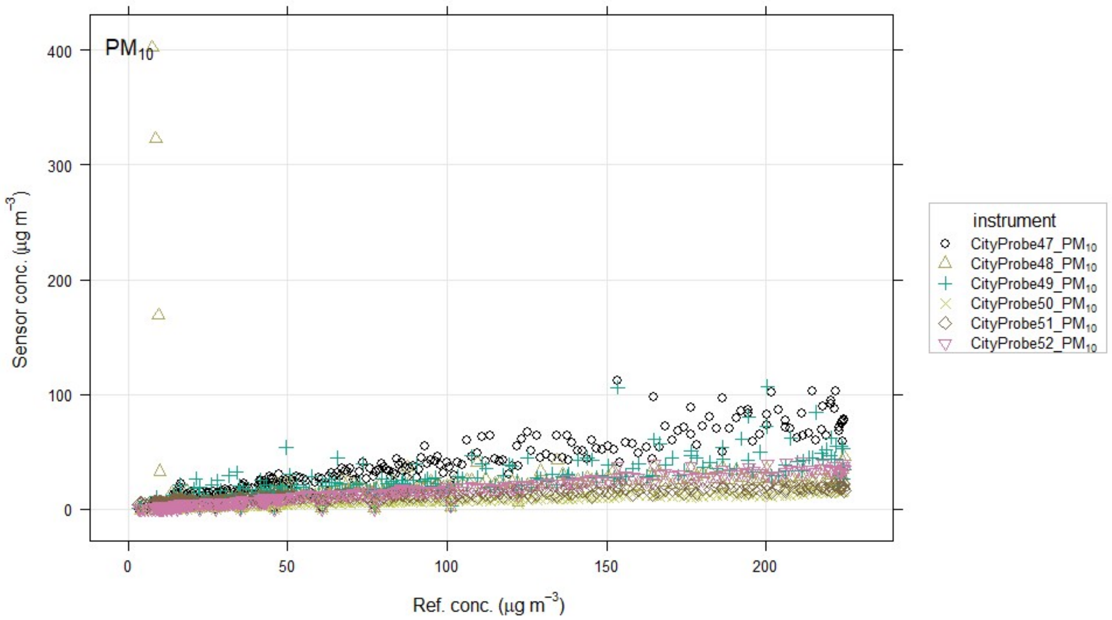


Figure 5. Correlation between concentrations measured by the sensors versus reference concentration (TEOM PM_{10})

The scatterplot for PM_{10} measured by TEOM versus concentrations measured by the sensors is shown in **Figure 5**. It is evident that this size fraction is much less influenced by instrumental artefacts and noise (apart from a few outliers) compared to $PM_{2.5}$. For this size fraction, all sensors show good linearity.

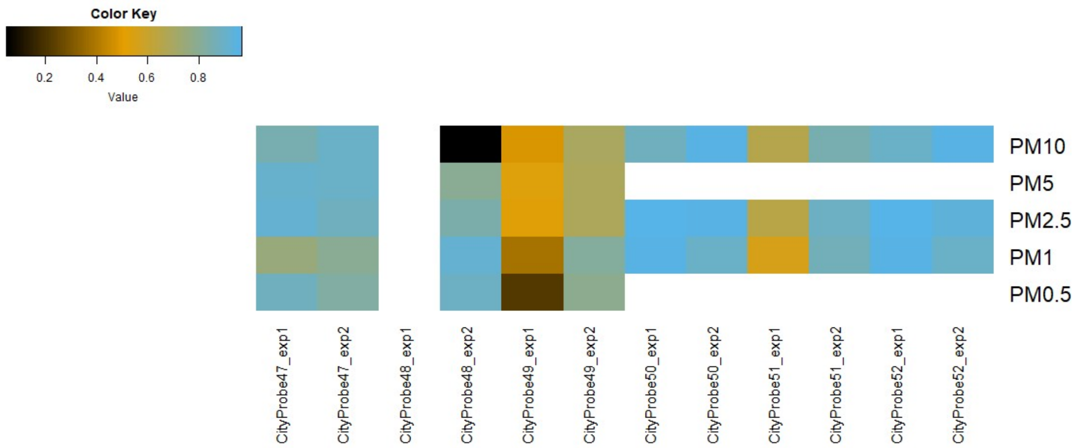


Figure 6. Heatmap of the coefficient of determination (R^2) for correlation between concentrations measured by the sensors and PM fractions measured by OPS.

A heatmap of the coefficient of determination (R^2) is shown in **Figure 6** for all sensors, all size fractions measured by OPS and TEOM and all experiments. It is again evident that both Sensirion and Piera sensors show good linearity with high R^2 (above 0.8, in some cases above 0.9). There is no clear trend among size fractions. It is however also evident that attention should be paid to instrumental artefacts as *e.g.* CityProbe-49 is performing poorly in the first experiment whereas it is showing reasonable performance in the second experiment. The same can be seen for CityProbe 48 where the value for PM_{10} is an outlier.

4.3. Bias

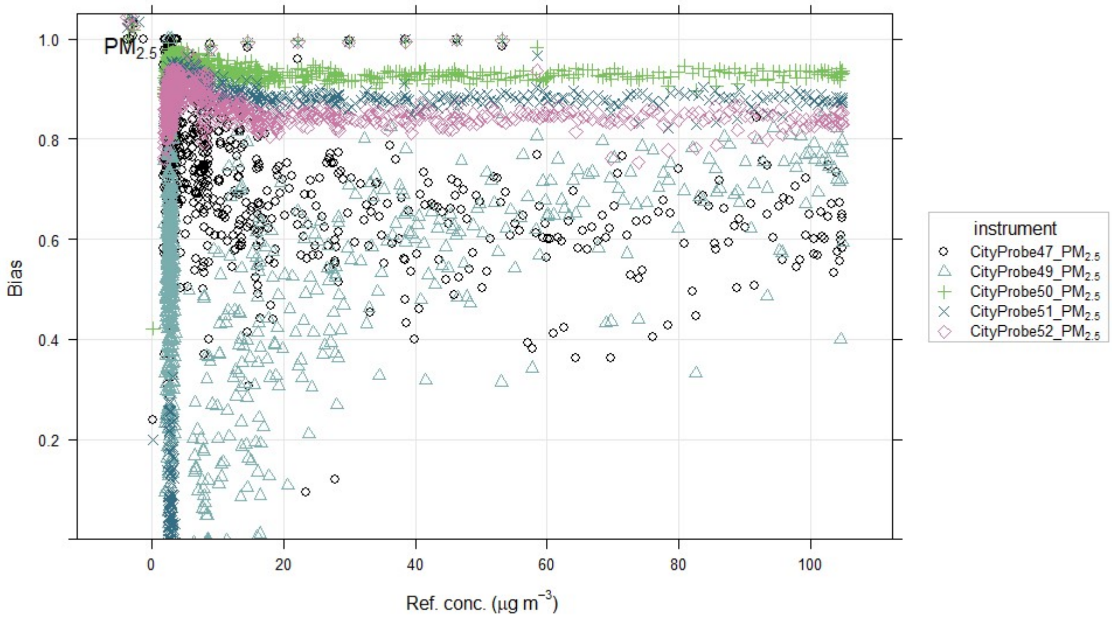


Figure 7. Bias between the low-cost sensors and reference instrument (TEOM $PM_{2.5}$)

An example of a scatterplot of the bias between the low-cost sensors and the reference instrument (TEOM $PM_{2.5}$) is shown in **Figure 7**. It is evident that all the sensors were subject to quite high biases between 50% and 100% (corresponding to 0.5-1 on the bias scale). It is likewise evident that the Sensirion sensors have the highest biases, but apart from the lowermost concentration range (lower than 20 $\mu g/m^3$), the biases of these sensors are relatively constant. This is in contrast to the Piera sensors, which both show large variations and non-linear behavior at the low concentrations. There is also a large sensor to sensor variation for the Sensirion sensors, which could benefit from individual calibrations.

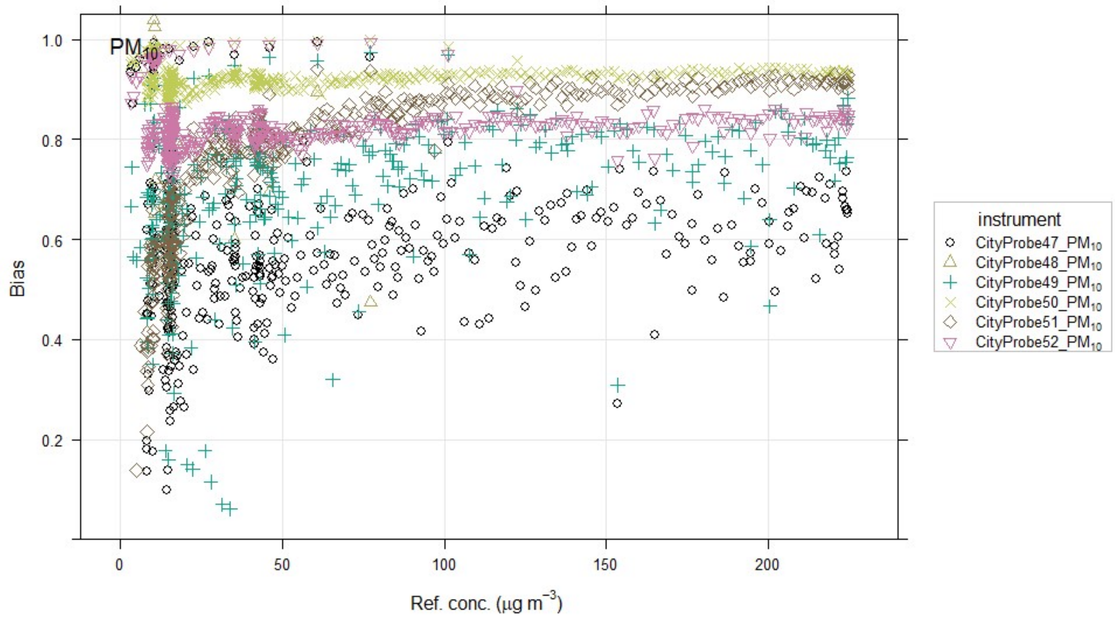
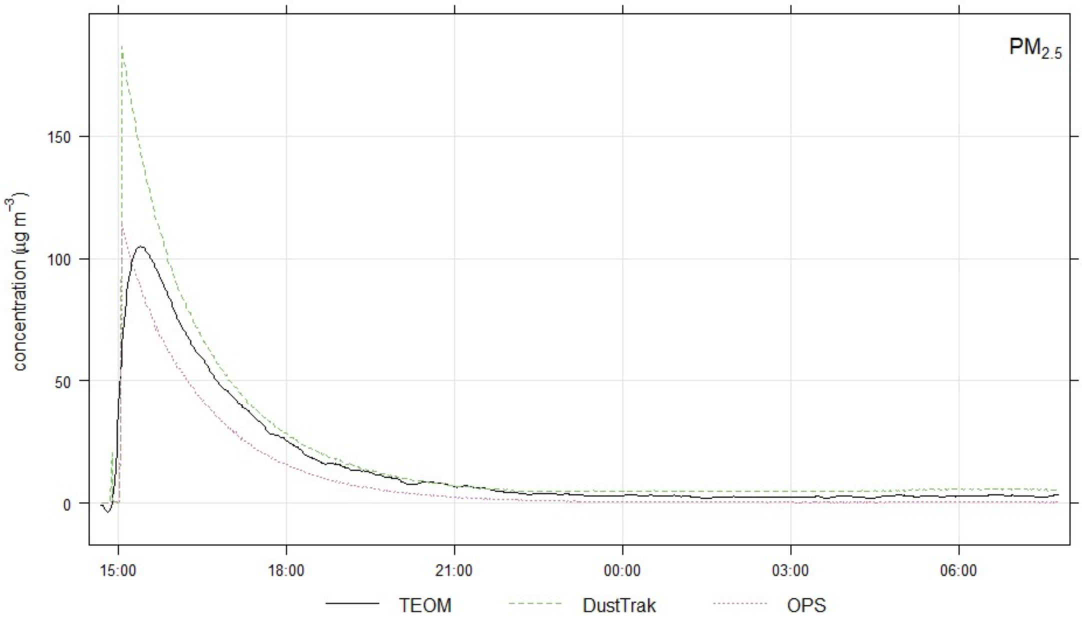


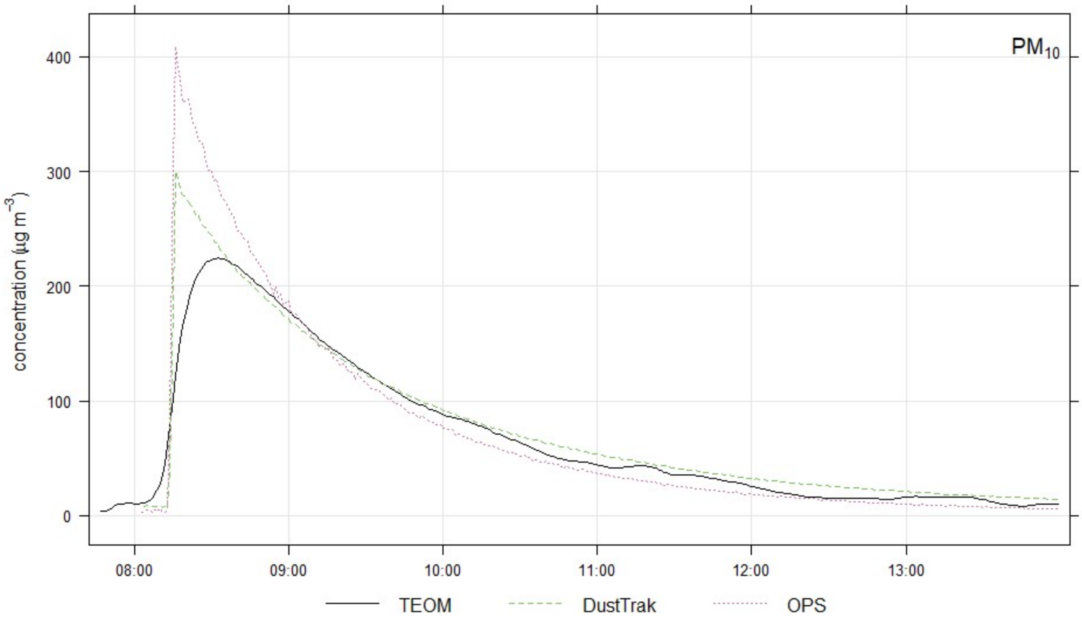
Figure 8. Bias between the low-cost sensors and reference instrument (TEOM PM_{10})

The scatterplot for PM_{10} bias shows some of the same trends as the one for $PM_{2.5}$ (**Figure 8**), however, CityProbe 51 is showing a non-linear bias for this size fraction which is different from the results for $PM_{2.5}$.

5. Appendix

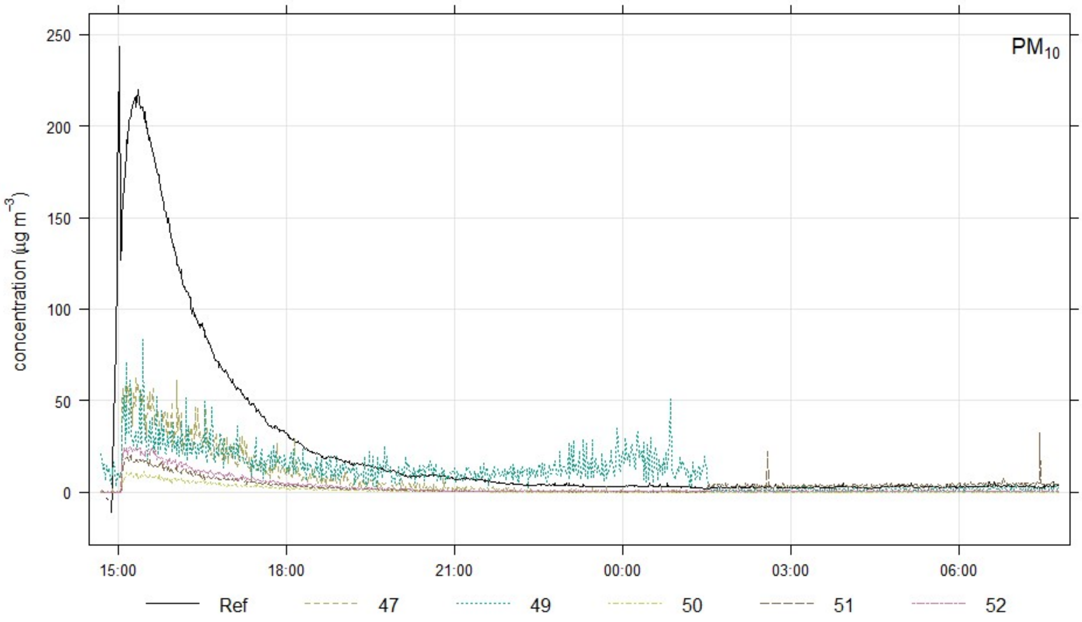
Comparison of reference data

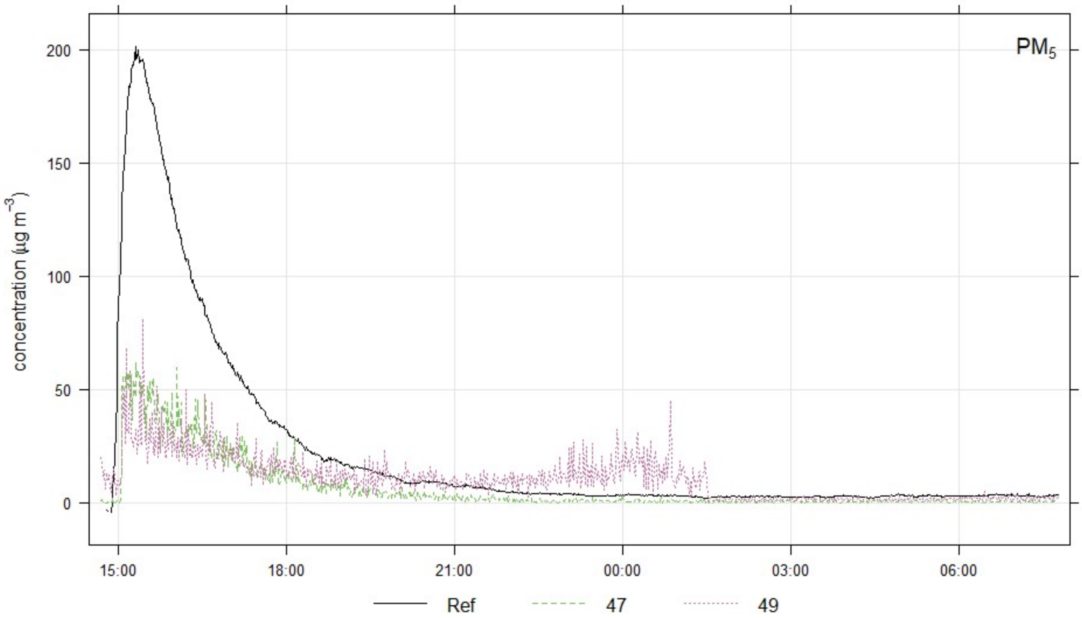


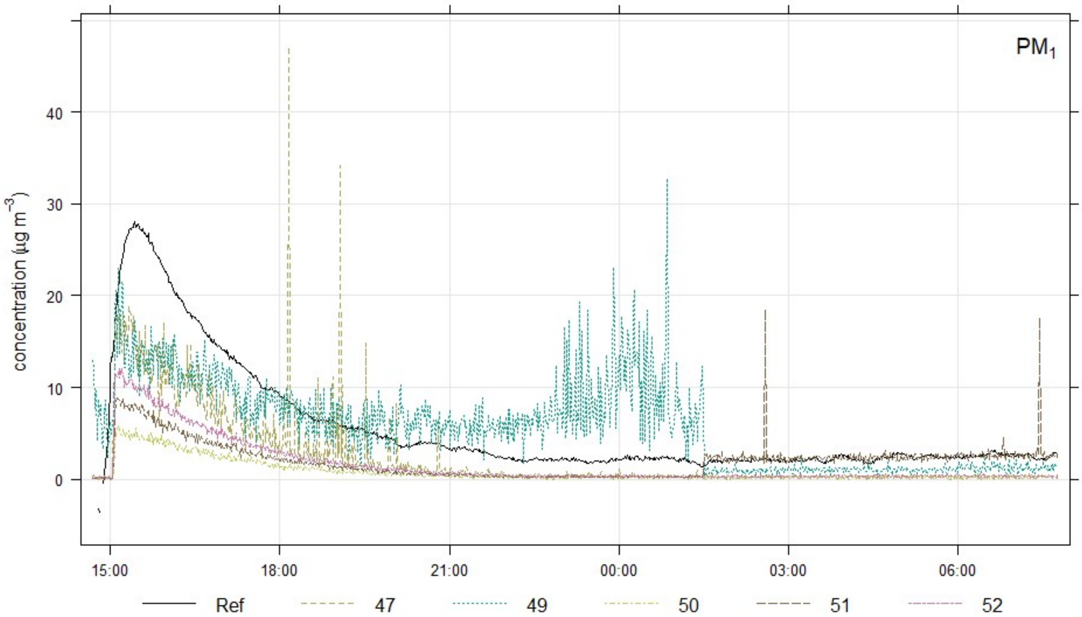


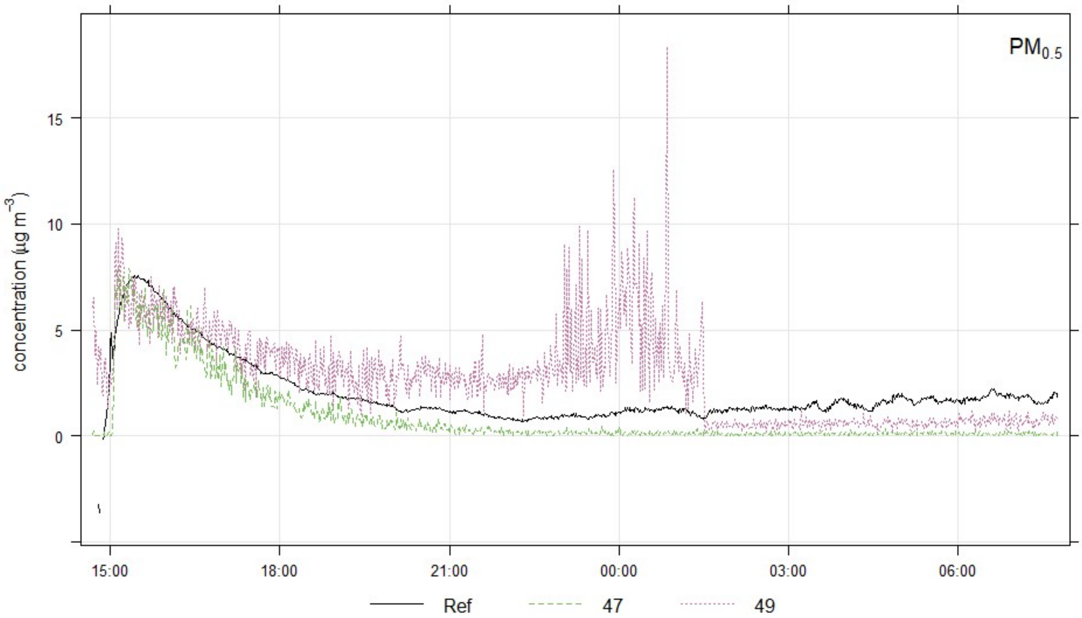
Time series

Experiment 1

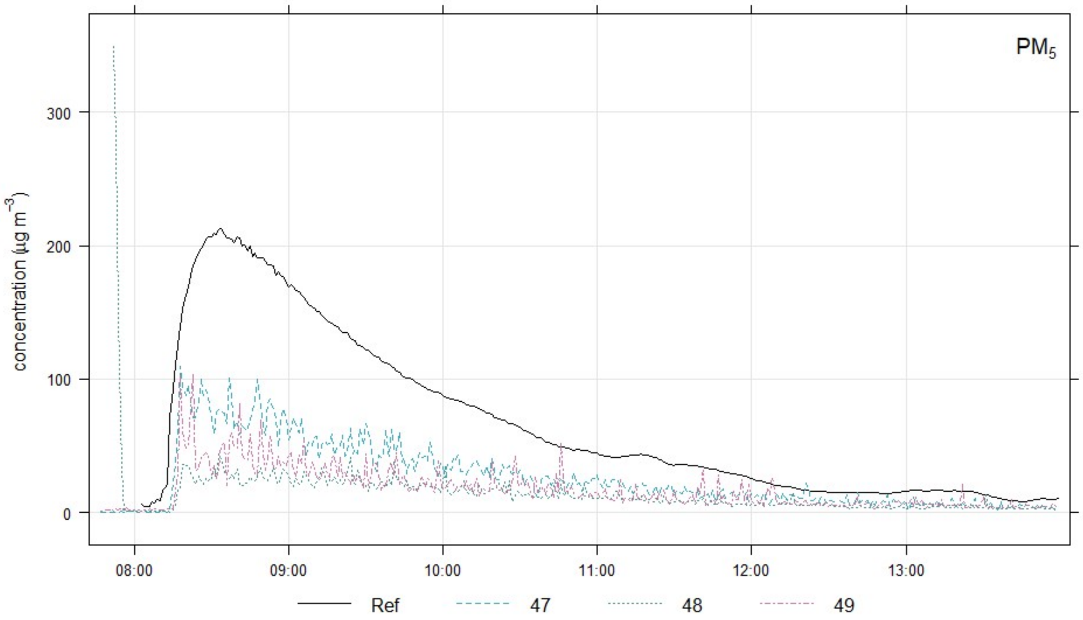


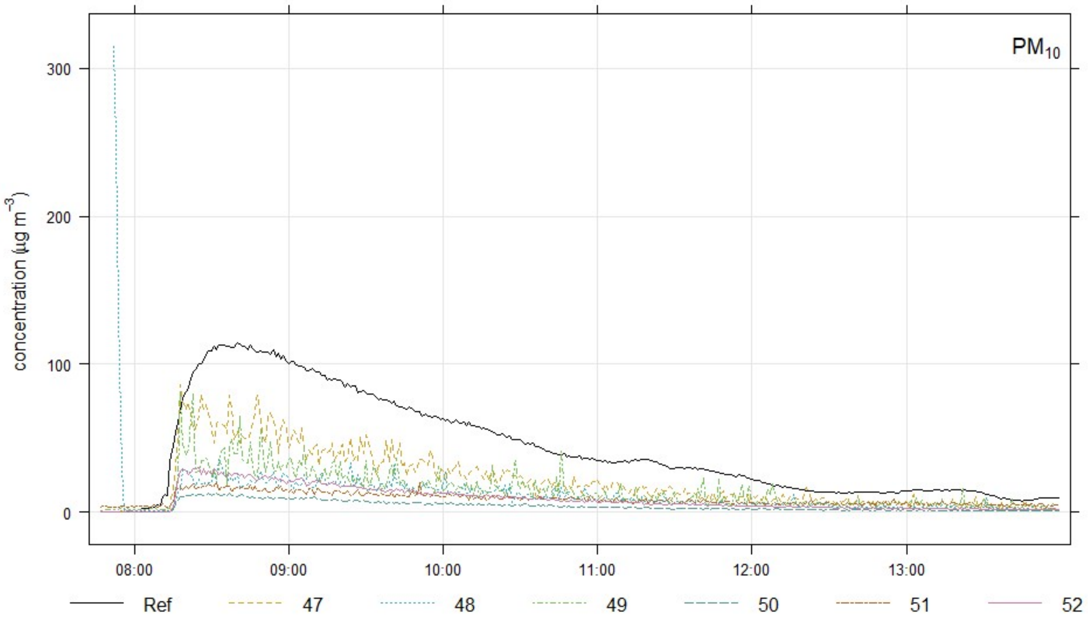


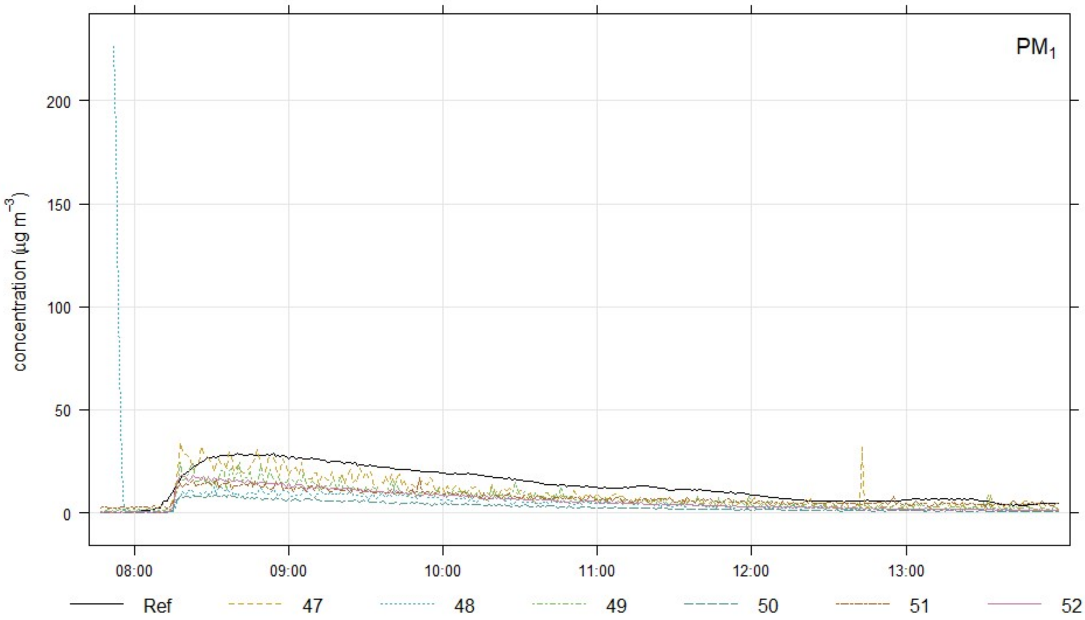

PM$_1$
concentration (μg m^{-3})
40
30
20
10
0
15:00
18:00
21:00
00:00
03:00
06:00
Ref
47
49
50
51
52

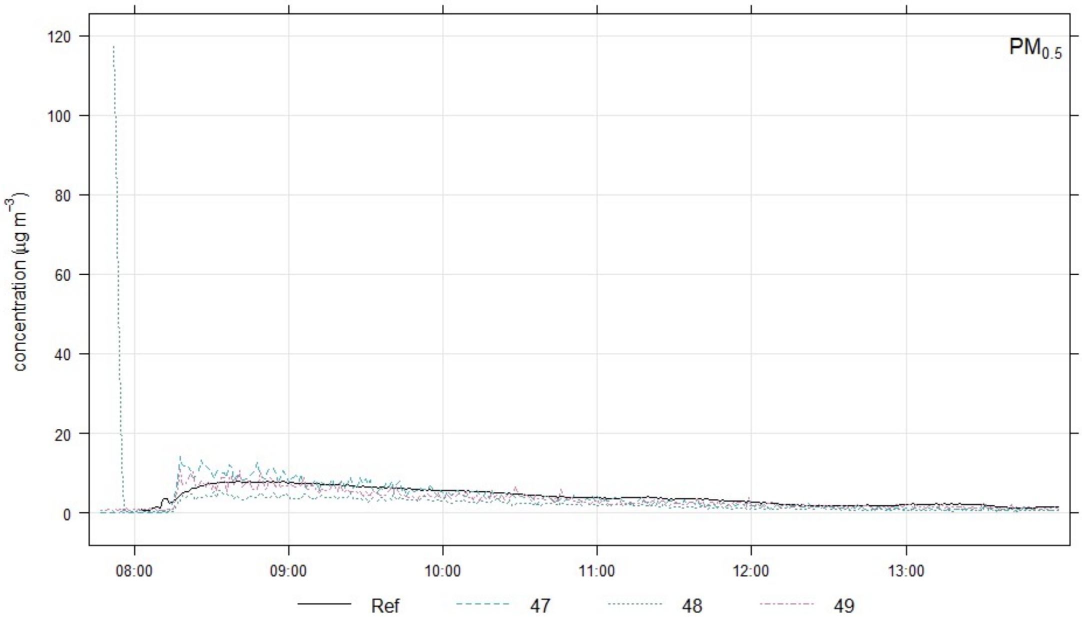

PM$_{0.5}$
concentration (μg m^{-3})
15
10
5
0
15:00
18:00
21:00
00:00
03:00
06:00
Ref
47
49

Experiment 2



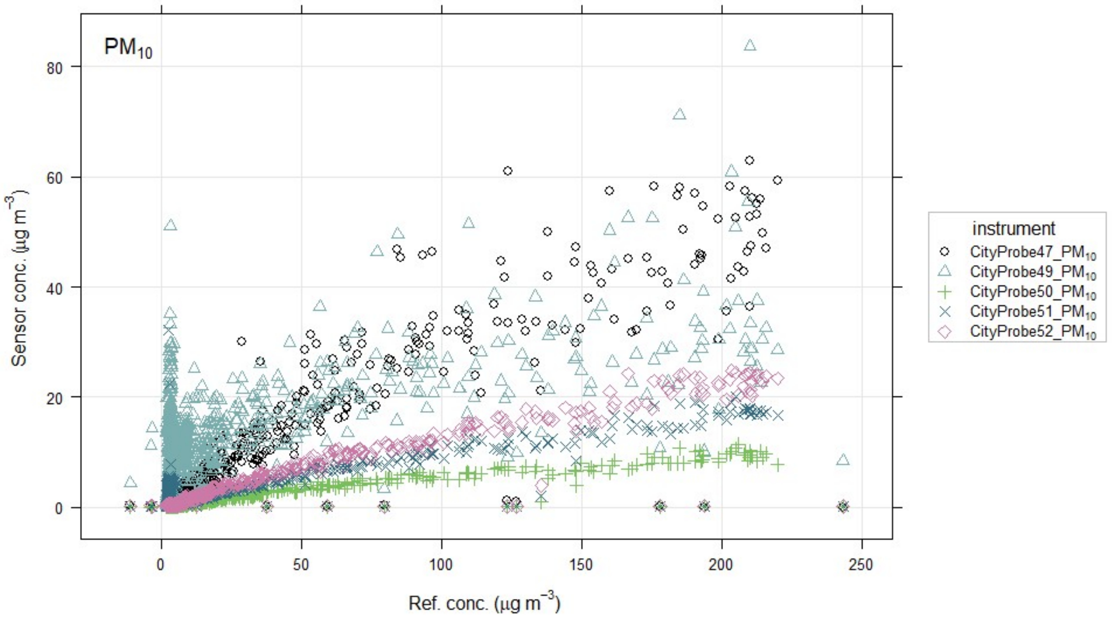


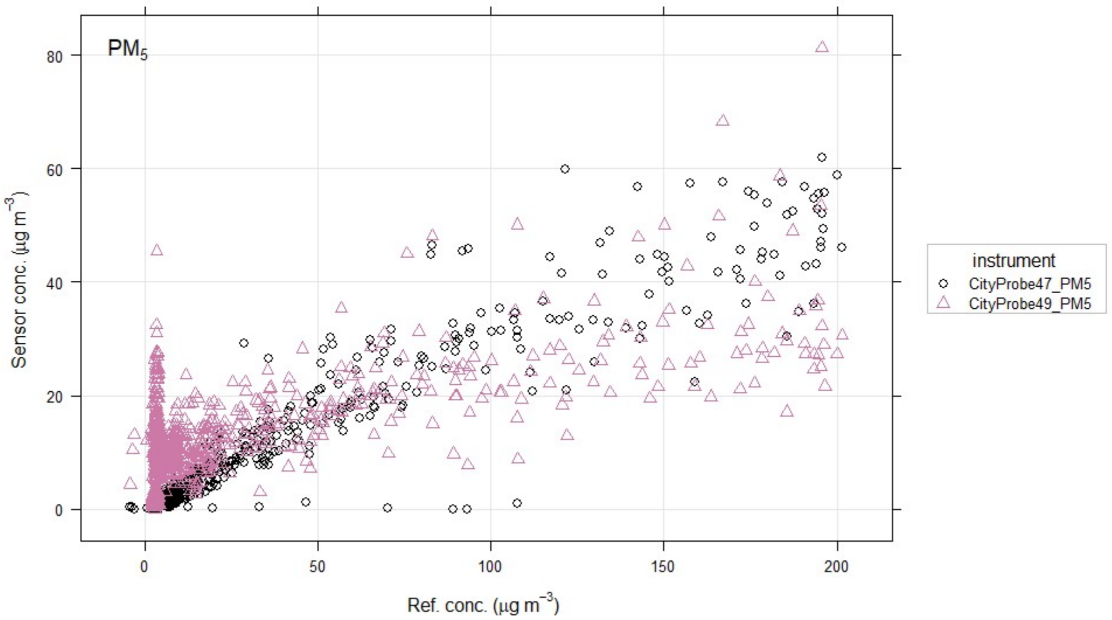

PM1
concentration (µg m-3)
0
50
100
150
200
08:00
09:00
10:00
11:00
12:00
13:00
Ref
47
48
49
50
51
52

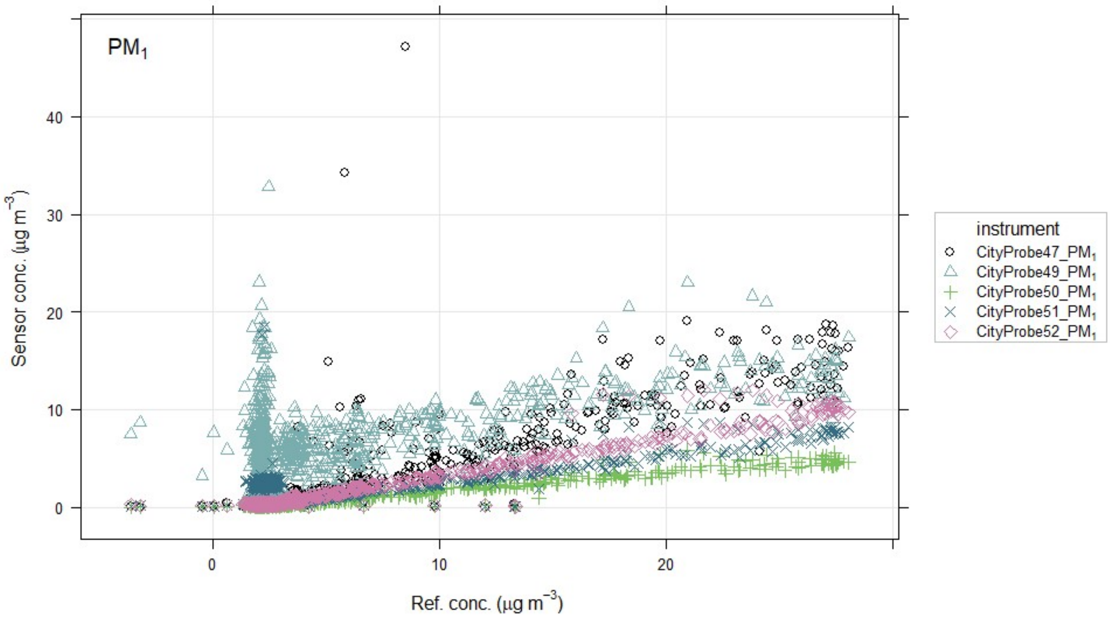

PM0.5
concentration (µg m-3)
0
20
40
60
80
100
120
08:00
09:00
10:00
11:00
12:00
13:00
Ref
47
48
49

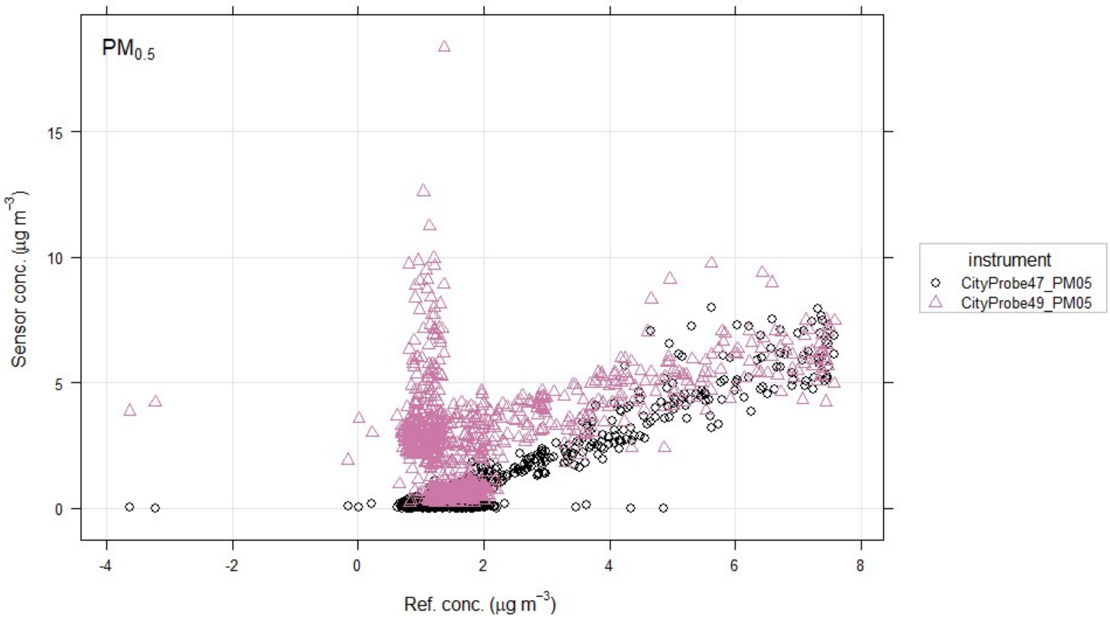
Scatterplots

Experiment 1

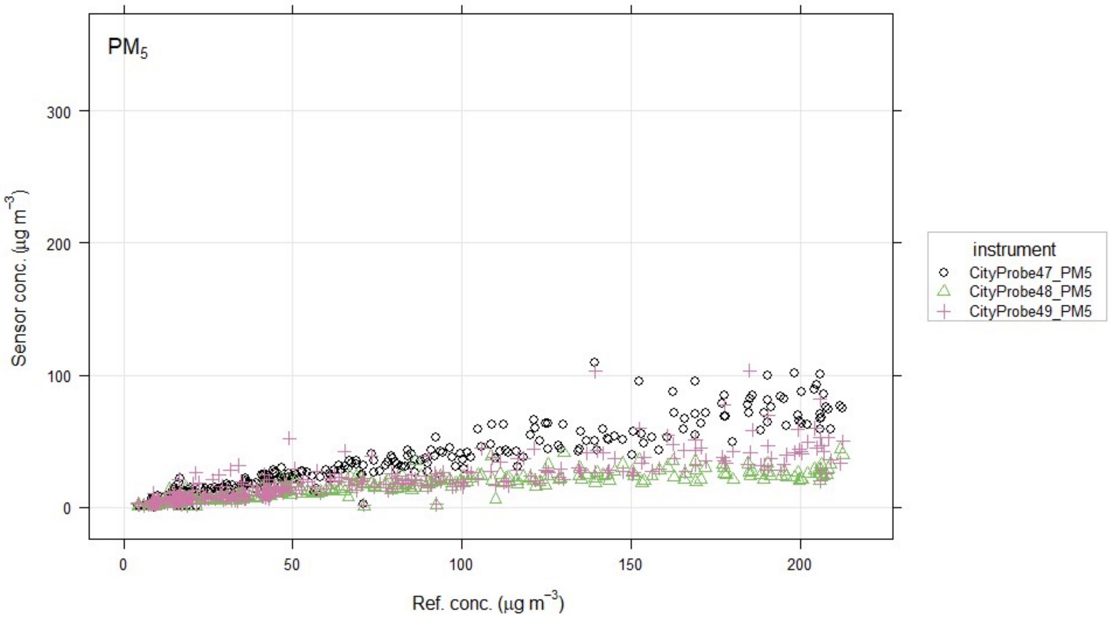


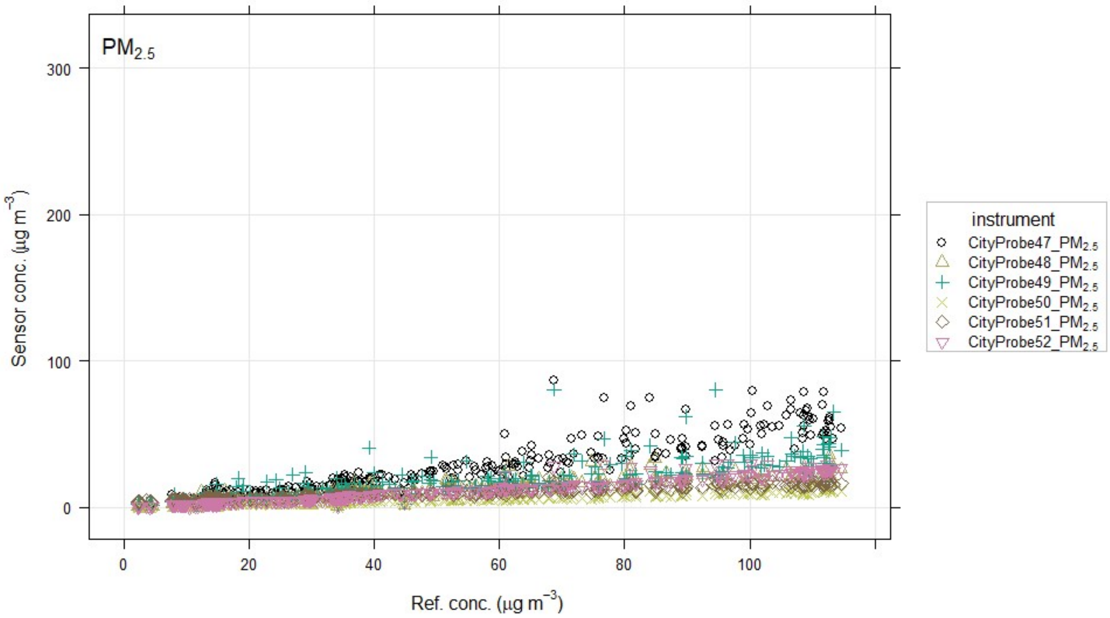


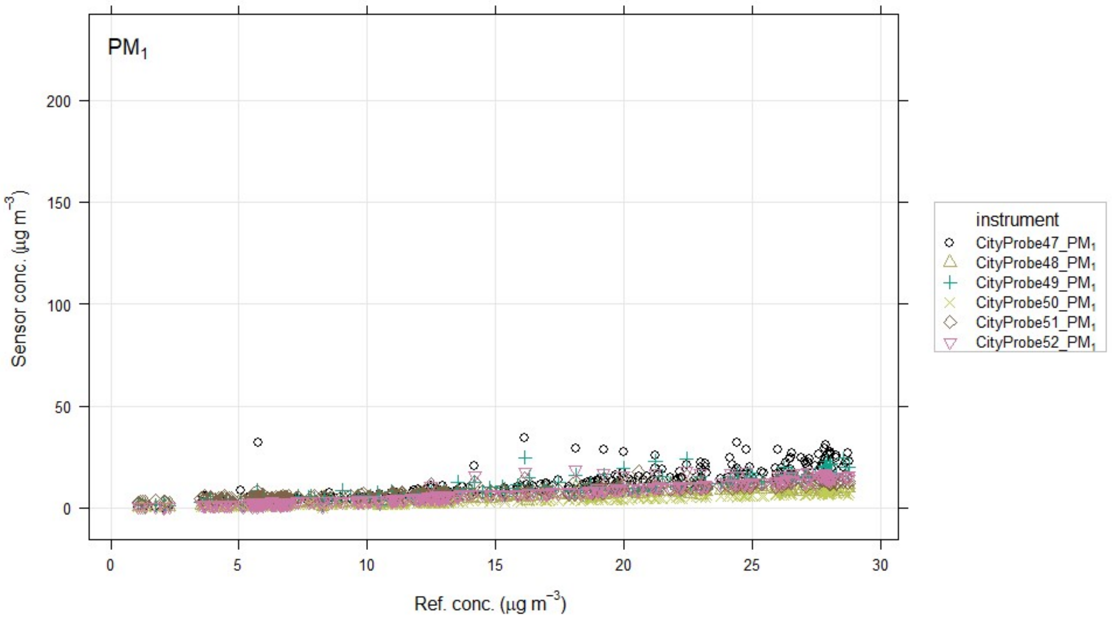

PM1
Sensor conc. (µg m-3)
Ref. conc. (µg m-3)
0
10
20
30
40
instrument
CityProbe47_PM1
CityProbe49_PM1
CityProbe50_PM1
CityProbe51_PM1
CityProbe52_PM1

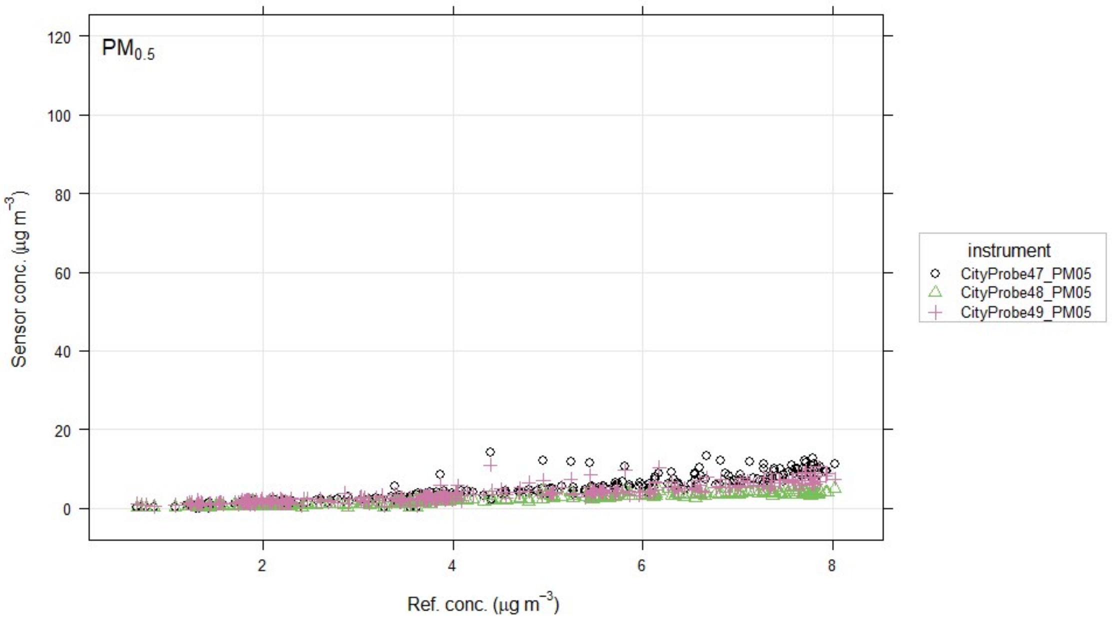

PM0.5
Sensor conc. (µg m-3)
Ref. conc. (µg m-3)
-4
-2
0
2
4
6
8
5
10
15
instrument
CityProbe47_PM05
CityProbe49_PM05

Experiment 2



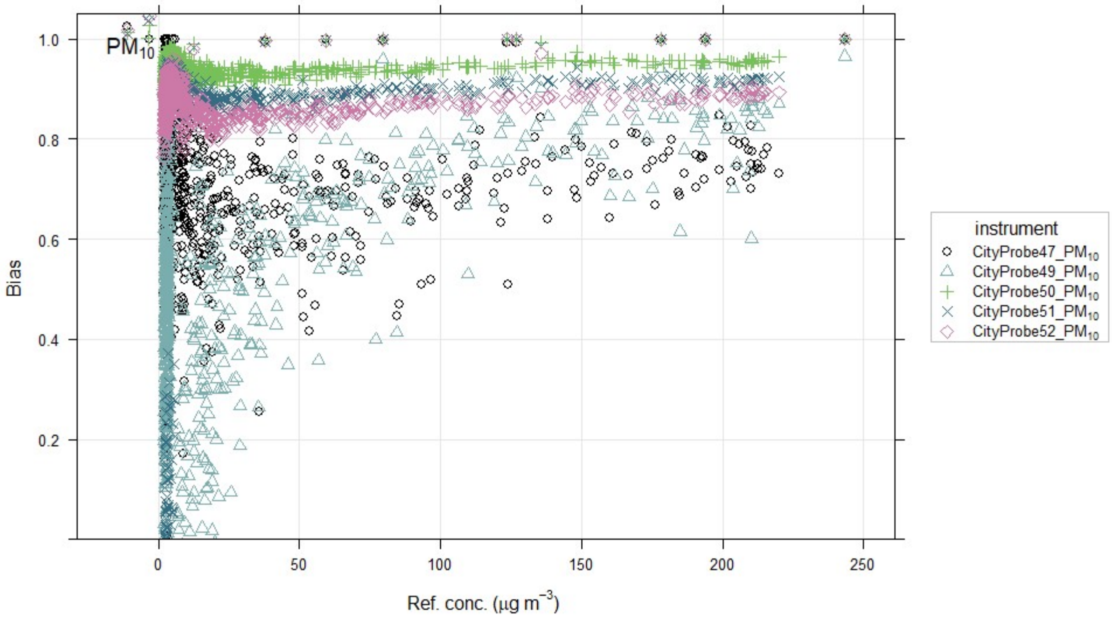


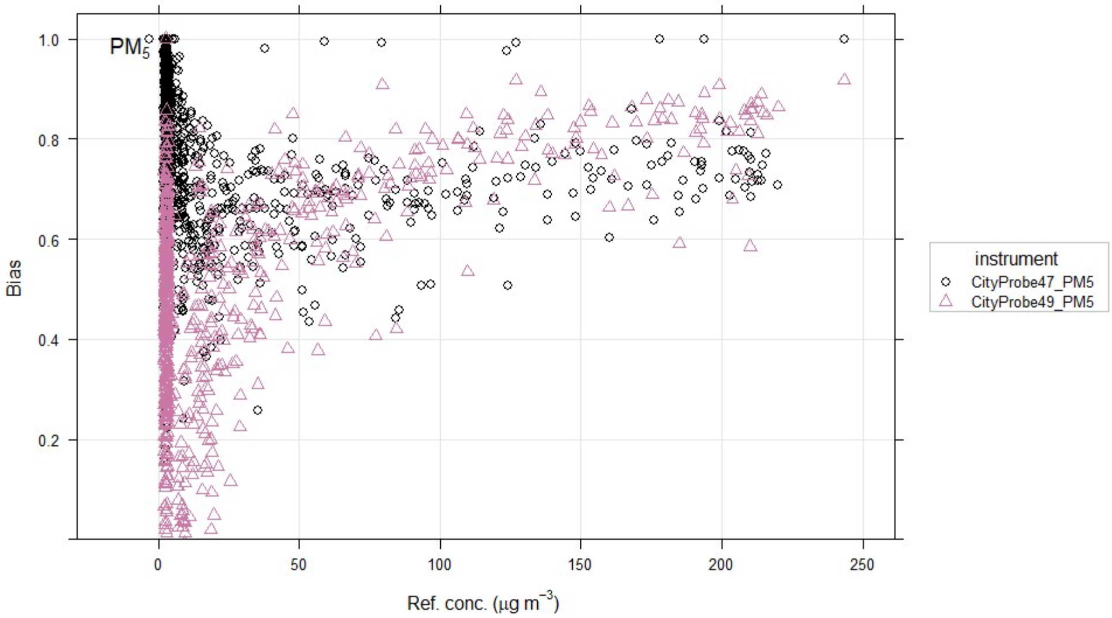

PM1
200
150
100
50
0
0
5
10
15
20
25
30
Sensor conc. (µg m-3)
Ref. conc. (µg m-3)
instrument
CityProbe47_PM1
CityProbe48_PM1
CityProbe49_PM1
CityProbe50_PM1
CityProbe51_PM1
CityProbe52_PM1

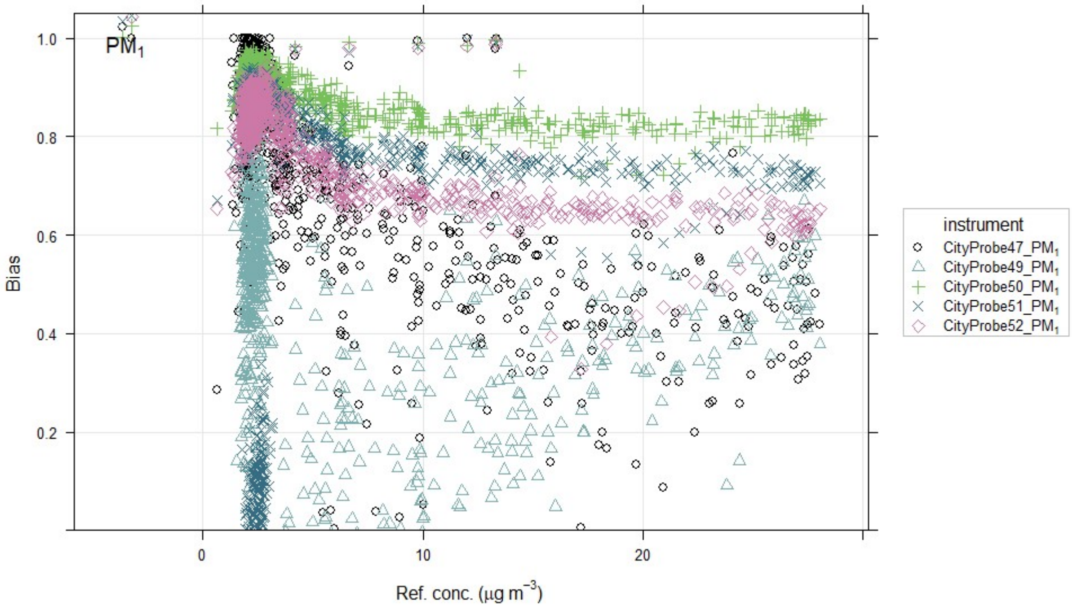

PM0.5
120
100
80
60
40
20
0
2
4
6
8
Sensor conc. (µg m-3)
Ref. conc. (µg m-3)
instrument
CityProbe47_PM05
CityProbe48_PM05
CityProbe49_PM05

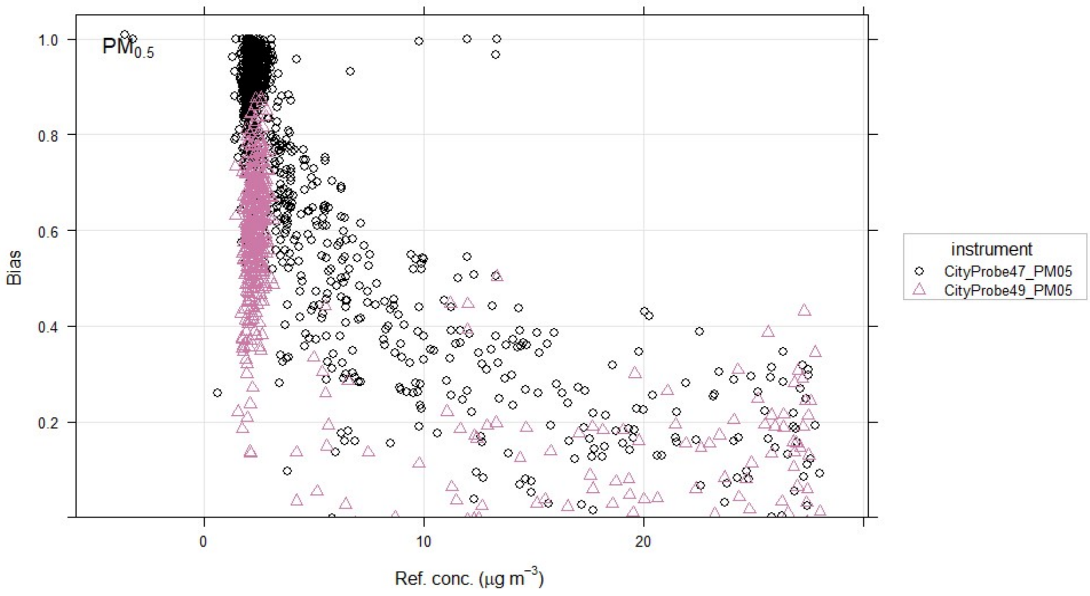
Bias

Experiment 1

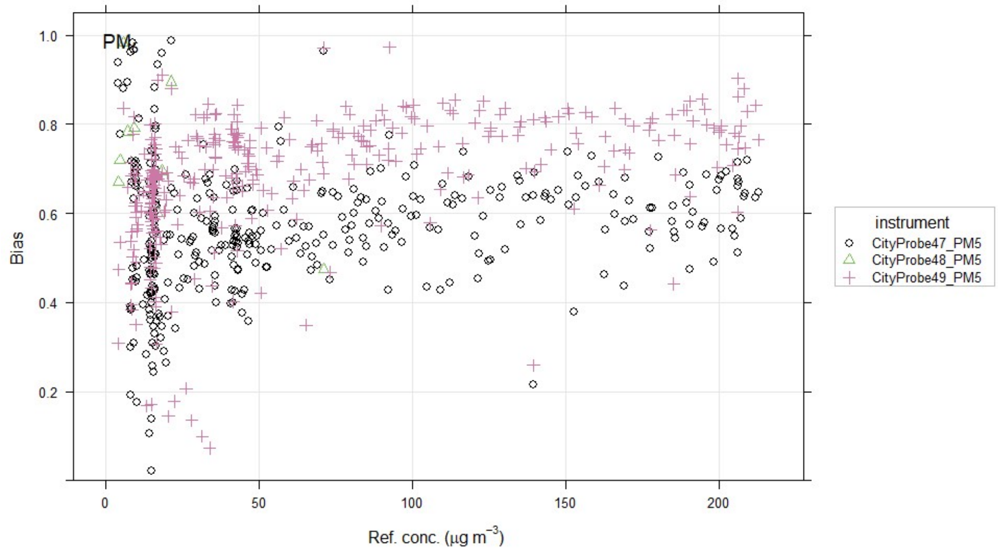


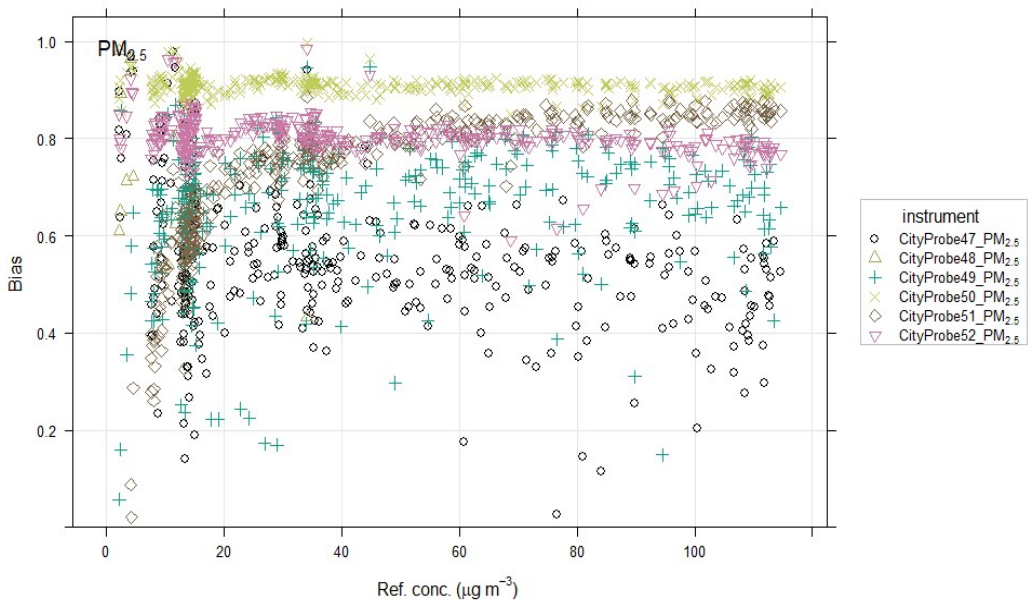


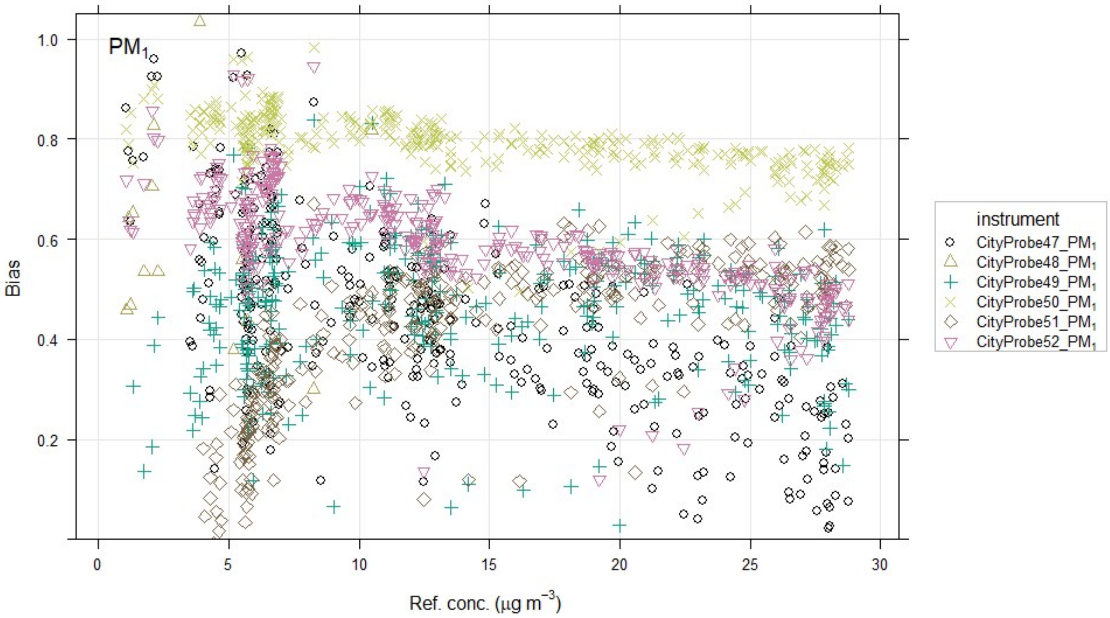

PM1
1.0
0.8
0.6
0.4
0.2
Bias
0
10
20
Ref. conc. (µg m⁻³)
instrument
CityProbe47_PM1
CityProbe49_PM1
CityProbe50_PM1
CityProbe51_PM1
CityProbe52_PM1

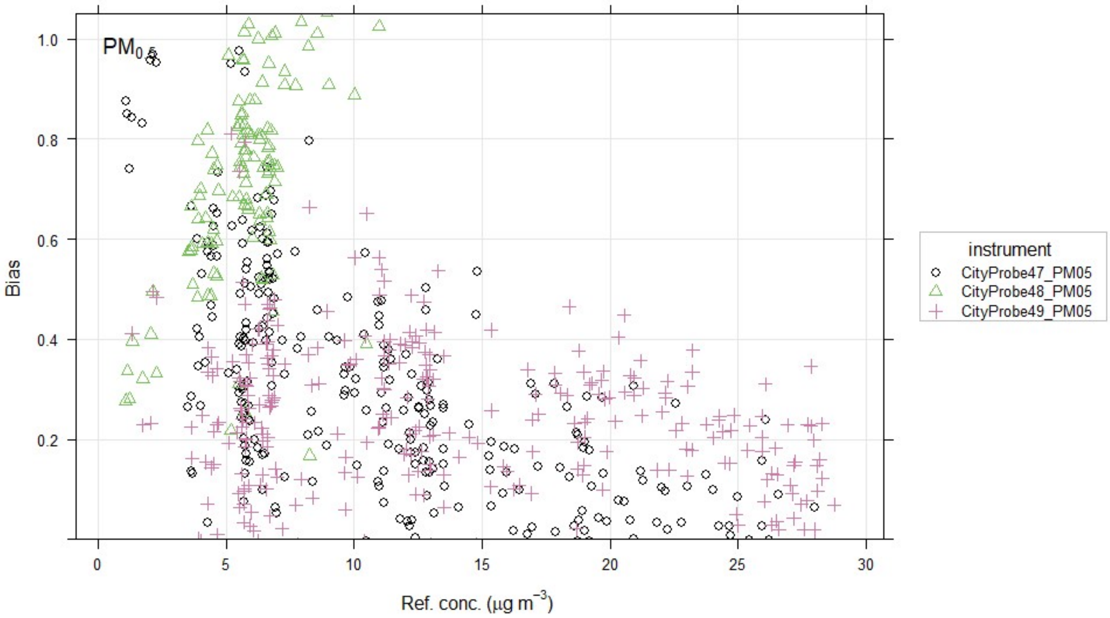

PM0.5
1.0
0.8
0.6
0.4
0.2
Bias
0
10
20
Ref. conc. (µg m⁻³)
instrument
CityProbe47_PM05
CityProbe49_PM05

Experiment 2






PM1
Bias
Ref. conc. (µg m-3)
instrument
CityProbe47_PM1
CityProbe48_PM1
CityProbe49_PM1
CityProbe50_PM1
CityProbe51_PM1
CityProbe52_PM1


PM0.5
Bias
Ref. conc. (µg m-3)
instrument
CityProbe47_PM05
CityProbe48_PM05
CityProbe49_PM05

TEKNOLOGISK
INSTITUT