Validatie van luchtkwaliteitssensoren

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Outline

- Introduction to AQ sensors
- CEN Standardisation work on sensor testing
- Test infrastructure for sensor testing @VITO
- Results of sensor testing
- Concluding remarks

Introduction

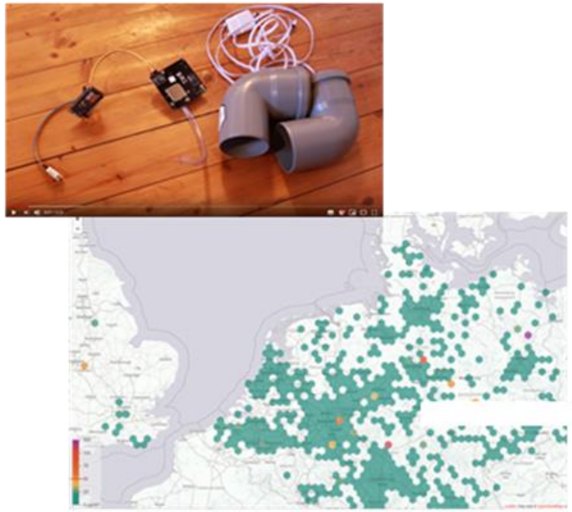
Why sensors?

- Sensors are additional tools for relative cheap measurements in addition to fixed AQMN
- Have high temporal resolution and can be deployed in denser networks
- Reliability of sensor data?
- Need for uniform test protocol and requirements

From measuring compound to integrated system

Sensors

Different types
Measuring unit

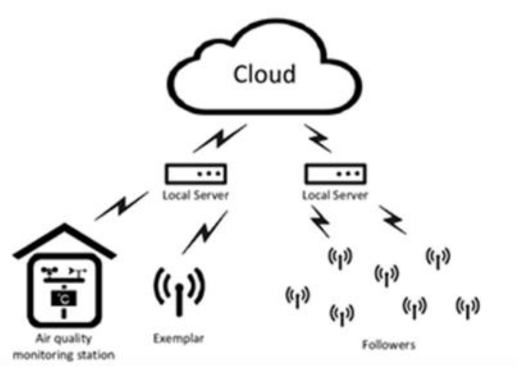


DIY building blocks

sensor, Arduino,
dataportal

Integrated systems

Sensor unit, database and dataportal,
calibration factors
visualisation



Hybrid systems

Sensor network
using also additional data
(a.o. AQMN, models)

How reliable are sensors?

What do we need?

How are they tested?

Evaluation parameter?

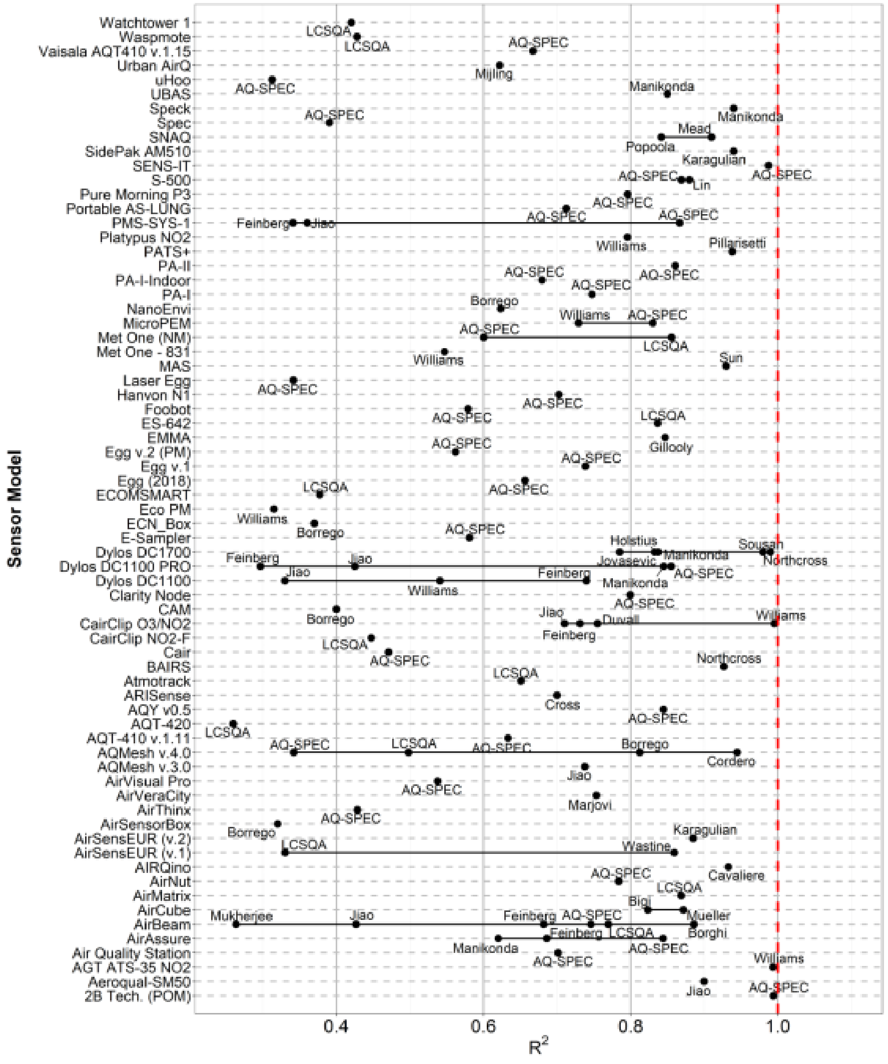
Operating conditions?

Calibrated?

Data processing?

Test results can be quite different

- Different result for different test protocol
- Different evaluation metrics
  - R^2
  - Slope, intercept
  - RMSE, MAE,…
  - Expanded uncertainty
  - …
- Different test conditions
  - Concentration ranges
  - Meteorological conditions
  - Interferences
  - Composition/size of PM



Karagulian et al., Atmosphere 2019, 10, 506

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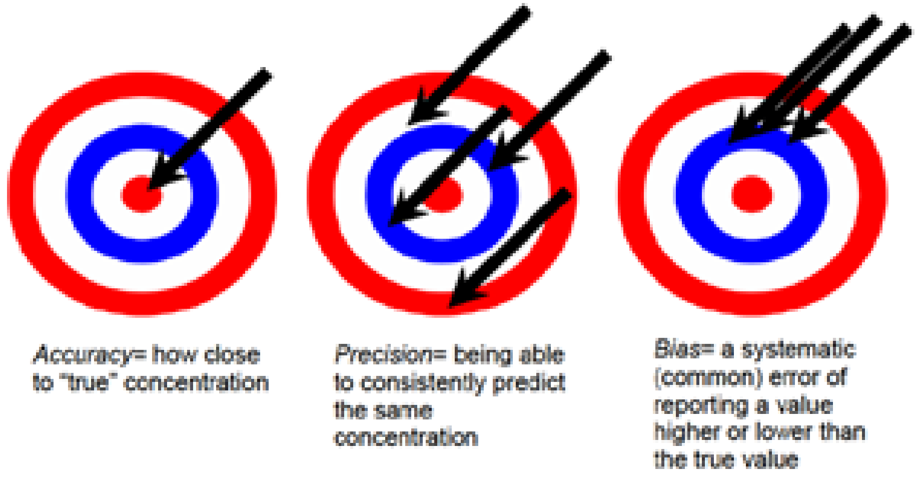
The required data quality is function of the application

- Fit for purpose!
- Measurement set-up is also important
- Evaluation metric
- Data processing



CEN standardization work

CEN standardization work

- CEN TC 264/WG42
  - TC 264: Air Quality
  - WG42: Ambient Air – Air Quality Sensors

- Performance evaluation of AQ sensors

- Work is linked to the use of sensors related to the EU AQ Directive

EU Air Quality Directive

- EU Air Quality Directive: 2008/50/EC
  - Directive on air quality and cleaner air for Europe
  - Objectives for AQ limit values and **common methods** to assess AQ
  - **PM_{10}, $PM_{2,5}$, NO_2, CO, O_3, SO_2,** Pb, **Benzene**

- It includes Data Quality Objectives for measurement techniques:
  - Reference monitoring (fixed sampling points)
  - **Indicative measurements**
  - **Objective estimations**

→ **To supplement fixed sampling points**

Sensors can play a role here *(but NOT ONLY HERE)*

Towards a uniform test protocol for sensors in Europe

- **Question:** Can sensors meet the prescribed data quality objectives (DQO) of the EU Air Quality Directive?

  “Can sensors be used as indicative measurements or objective estimations”

- **Output:** a protocol describing specific **performance requirements** and **test methods** under prescribed laboratory and field conditions

- **Context:** using sensors as indicative measurements and objective estimations in EU reporting

Status standardization work on sensors in WG42

- Performance evaluation of air quality sensors

- Part 1 Gaseous pollutants in ambient air (NO_2, NO, CO, SO, O_3, benzene, CO_2)
  - **CEN/TS 17660-1 available**
  - TS -> CEN Standard

- Part 2 Particulate Matter in ambient air
  - In preparation
  - Expected to be ready for voting February 2024


Nederlandse voornorm

NVN-CEN/TS 17660-1
(en)

Luchtkwaliteit - Prestatiebeoordeling van sensorsystemen voor luchtkwaliteit - Deel 1: Gasvormige verontreinigingen in de buitenlucht

Air quality - Performance evaluation of air quality sensor systems - Part 1: Gaseous pollutants in ambient air

Data Quality Objectives (DQO)

DQO	O_3	CO, NO_2, SO_2	PM_{10}, $PM_{2.5}$
DQO Reference measurements	U = 15%	U = 15%	U = 25%
DQO Indicative measurements	U = 30%	U = 25%	U = 50%
DQO Objective estimations	U = 75%	U = 75%	U = 100%
	U = 200%	U = 200%	U= 200%

SENSOR CLASSES

→ CLASS 1

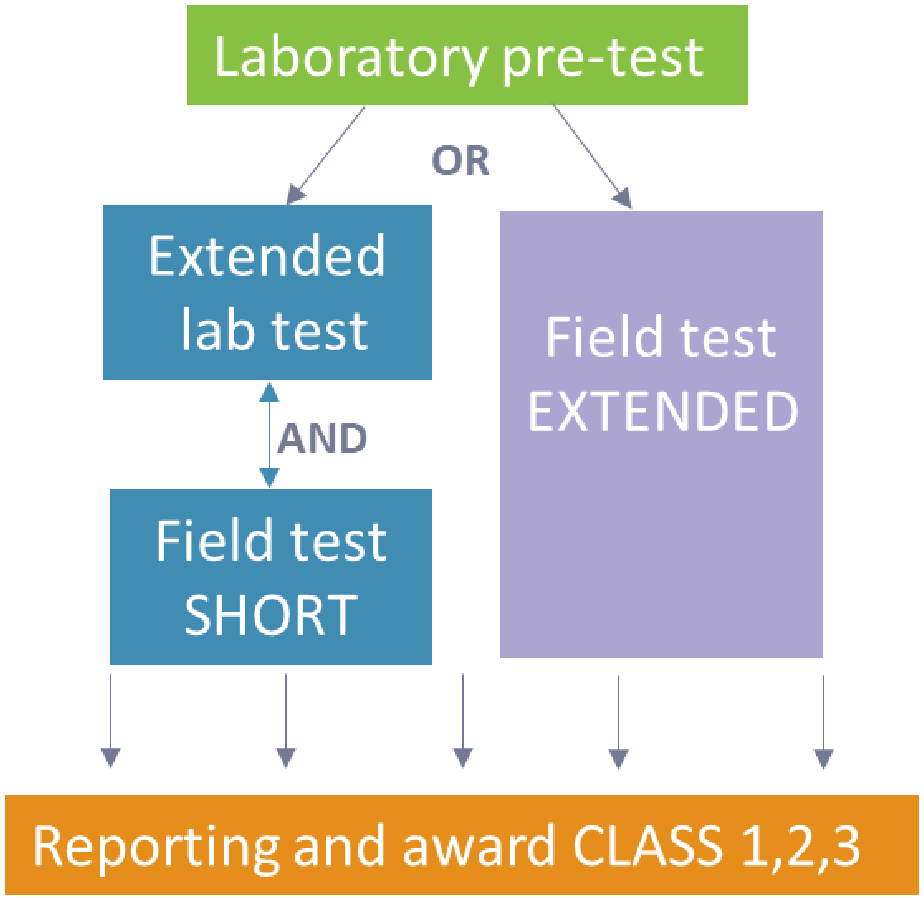
→ CLASS 2

→ CLASS 3

U: expanded uncertainty
Averaging time: period considered by the Limit Value (LV) -> 1h

Overview evaluation protocol (gas)

- Laboratory pre-test:
  - Response time, lack of fit, LOD, repeatability
- Extended lab tests
  - long-term drift
  - Cross-sensitivity of other pollutants
  - T and RH interference and hysteresis
  - Combined expanded uncertainty of lab tests
- Field test
  - Between sensor uncertainty
  - Data capture
  - expanded uncertainty of field tests => DQO at LV
- Sensor systems tested: 3 replicates



Protocol (gas)

- Laboratory tests:
  - Gas concentration levels
  - Interferences to be tested
  - Levels of T, RH :
    - T: 4 levels between -20 – 40°C
    - RH: 10-25%; 40-50%; 70-75%; 90%

- Field tests:
  - Number and type of test sites per pollutant
    - x2 for extended lab tests
  - Test conditions:
    - Meteorological conditions: 2 seasons (min 40 days)
    - Concentration levels
  - Installation, on-going quality control
  - Correction for slope and intercept

Classification of sensor systems

- Classification is based on **DQO** and **performance requirements**

- DQO (as maximum expanded uncertainty):
  - **Class 1**: DQO of indicative measurements
  - **Class 2**: DQO of objective estimations
  - **Class 3**: more relaxed (200%), not linked to Directive, e.g. for research, education, …

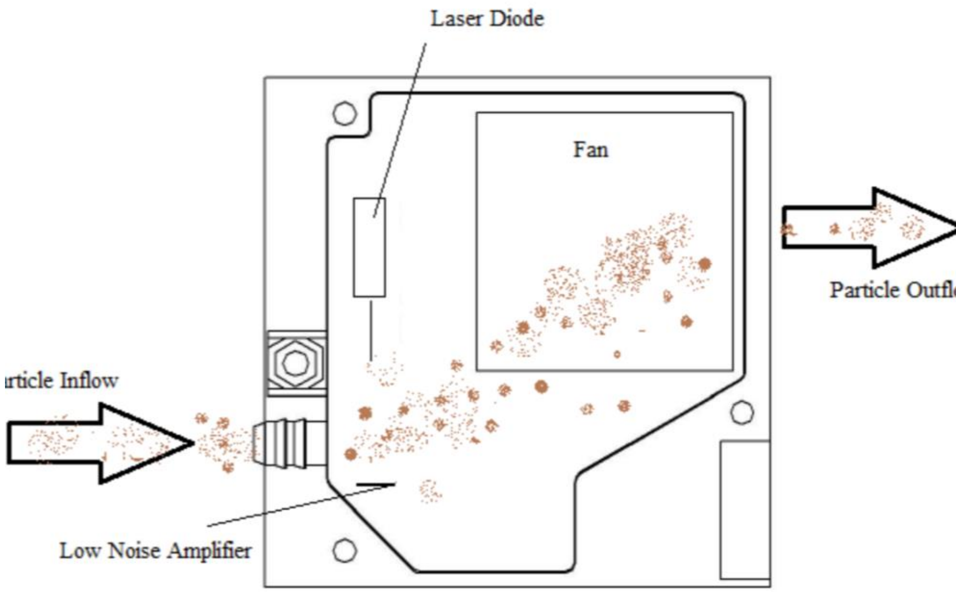
  - Evaluation based on DQO at LV (1h), time resolution is 1h if averaging period of LV is larger

- Requirements:
  - response time, lack of fit, repeatability, LOD
  - between sensor uncertainty, data capture

=> More stringent for Class1> Class 2> Class 3

Evaluation protocol for PM sensors

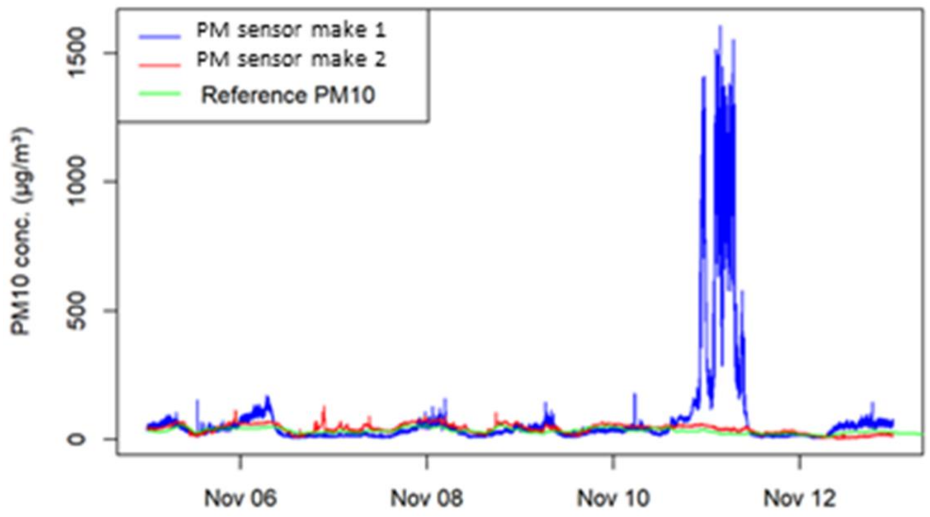
- Main differences with gases:
  - Reference method is filter based (24h)
  - PM ≠ gas
  - No extended lab tests, focus on field tests
- Laboratory test for coarse measurements
- Impact of RH on sensors needs to be evaluated



PMcoarse and RH issues

- $PM_{coarse} = PM_{10} - PM_{2.5}$
- Some sensors do not measure PM_{10} but calculate PM_{10} from measured $PM_{2.5}$
  - At most locations PM_{coarse} is relatively low
  - BUT these sensors do NOT pick up PM_{10} peak concentrations at occasions where PM_{coarse} is high

- RH: particle growth due to higher RH
- Some sensors overestimate PM readings at high RH
  - May be masked when only looking at 24h values if RH effect is compensated by ‘under’readings during other parts of the day



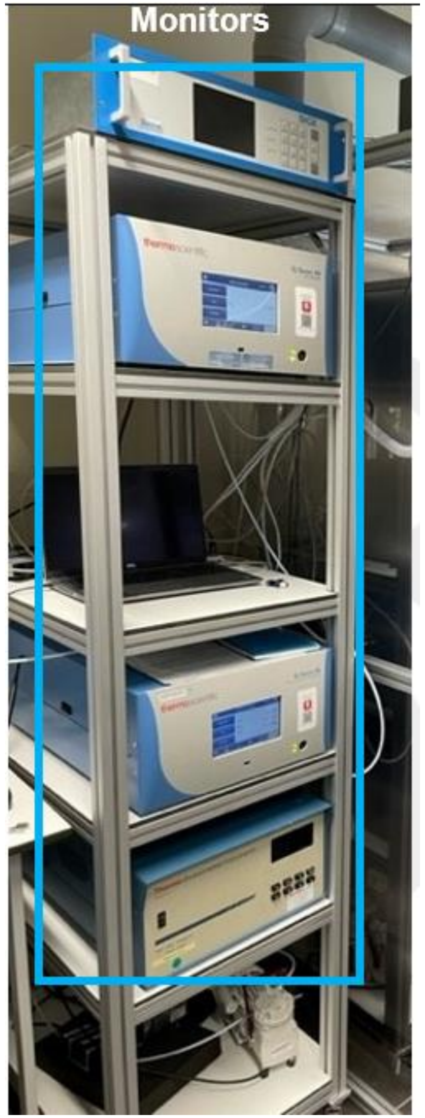
Test infrastructure @ VITO

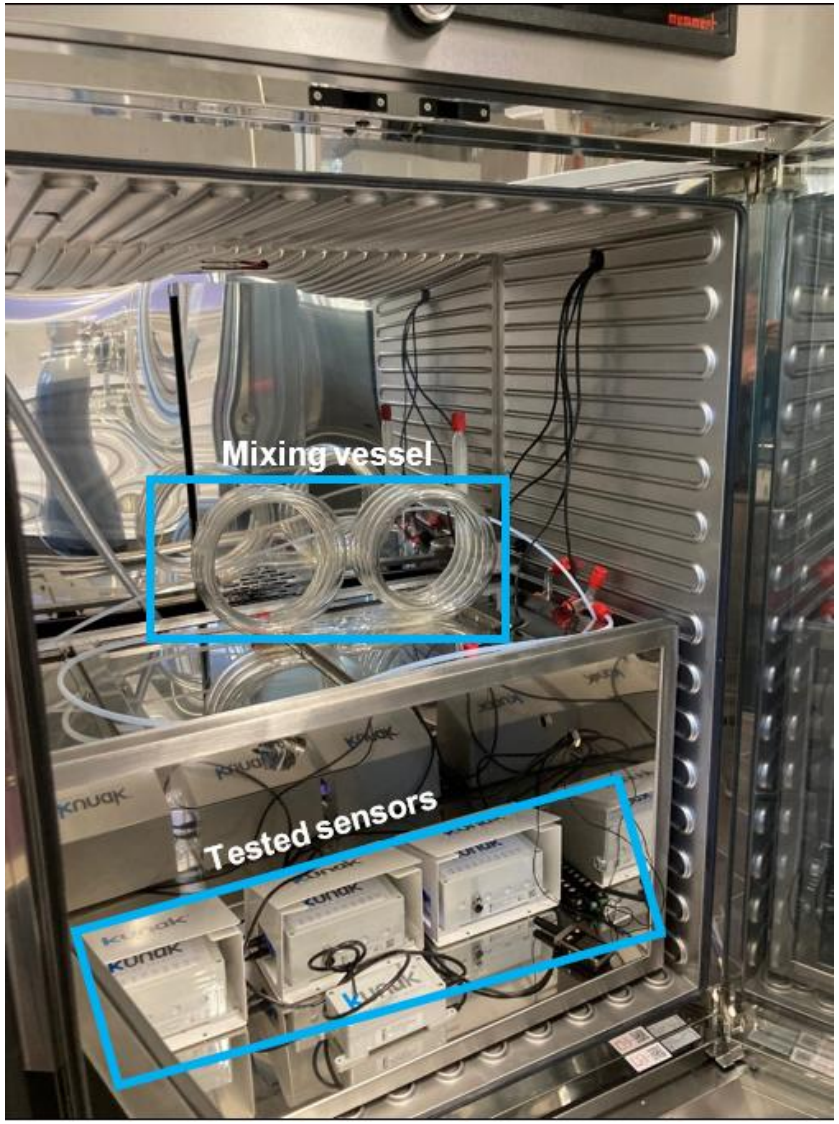
Requirements test chamber (gas) TS

- Requirements :
  - Stability of test gas and interferents (± 2%)
  - @ zero level: ± 3 ppb (± 0.1 ppm for CO)
  - T: ± 1°C
  - RH: ± 5%

- Reference concentrations based on:
  - Reference method
  - Calculated from gas generation

Gas test chamber





PM test chamber and generation

Sensors tested: projects

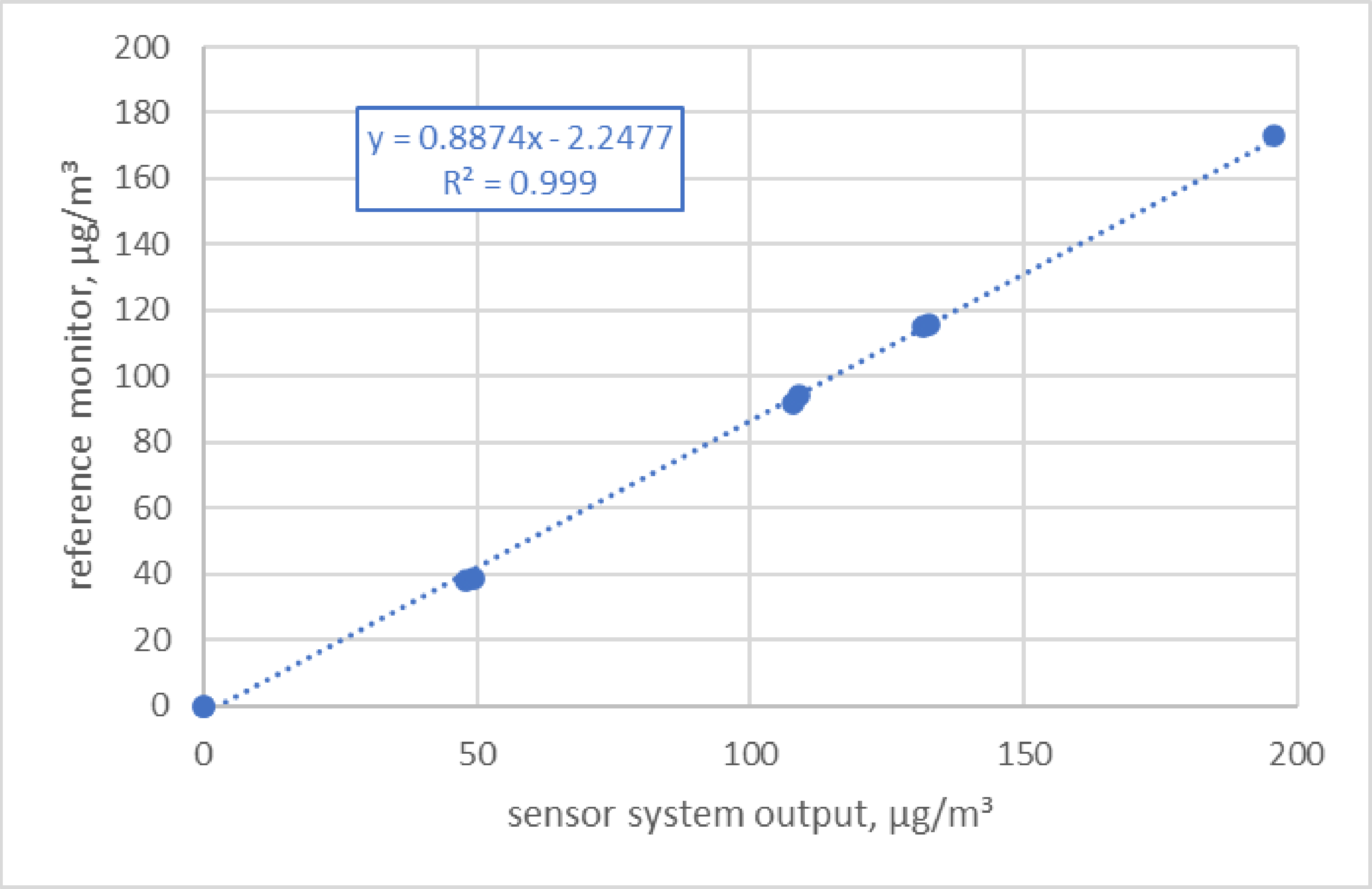
sensEURcity project (JRC)

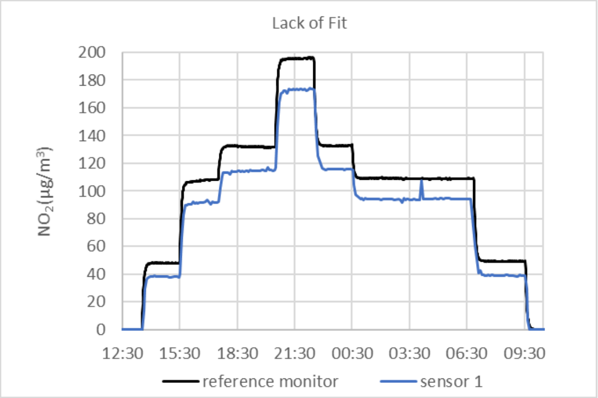
City of Things project (Kampenhout)

Benchmark study (VMM)

Test results

Lack of fit test





U(lof) = 3.5 µg/m³

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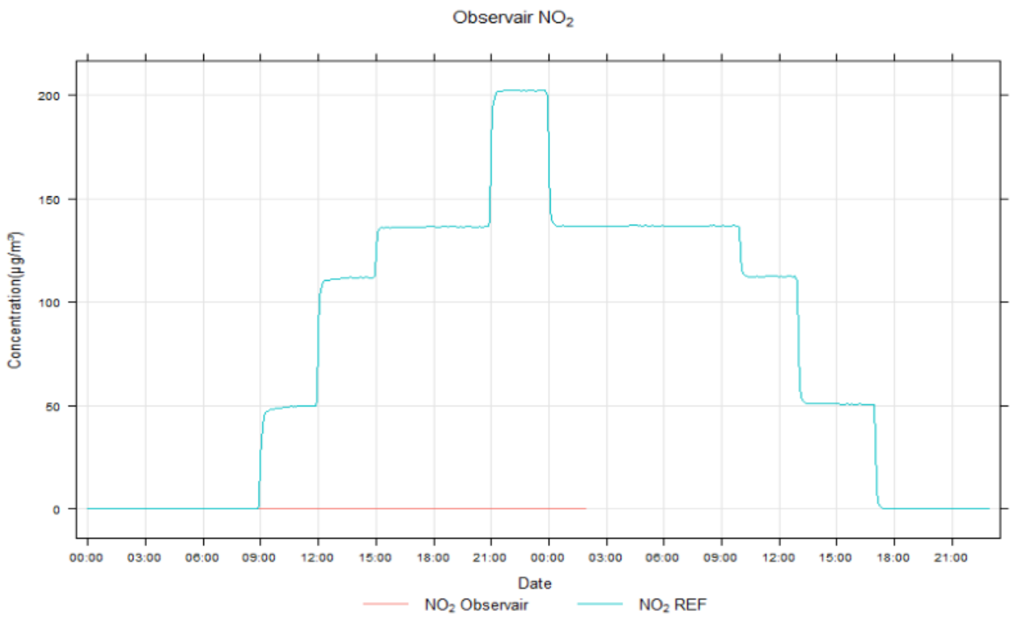
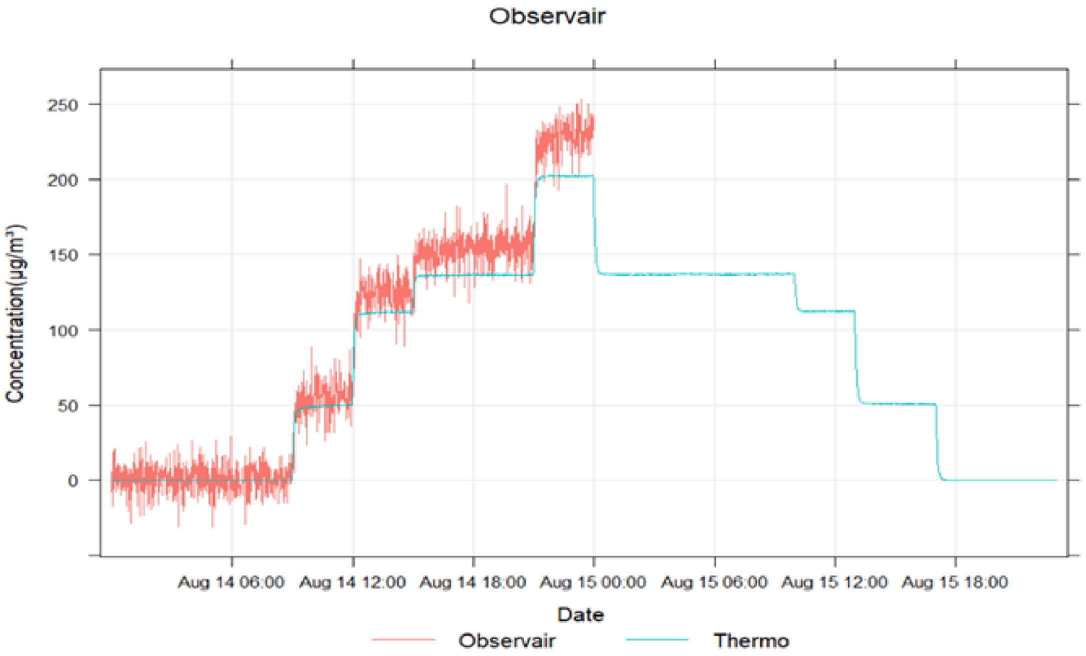
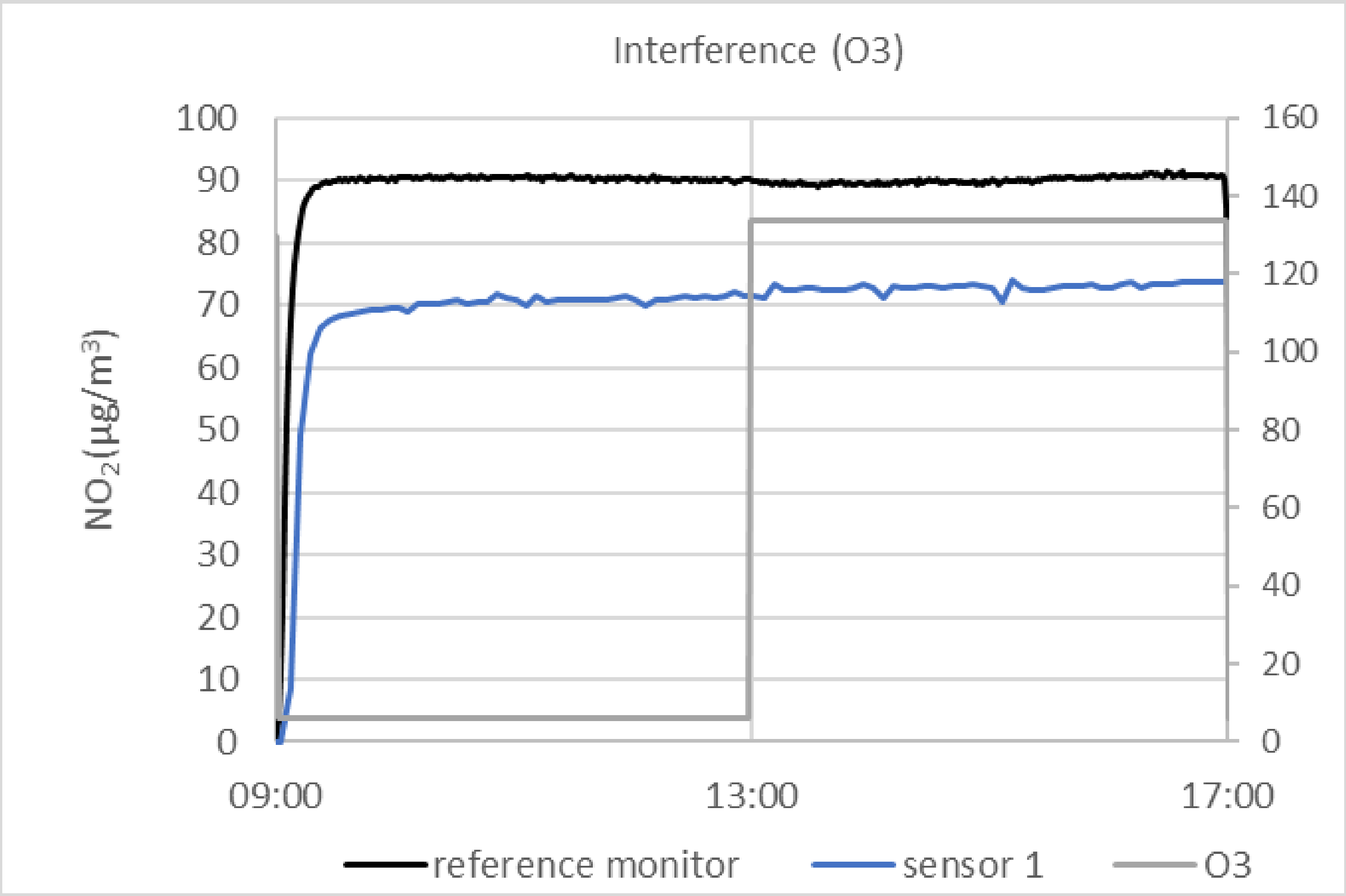
Lack of fit test



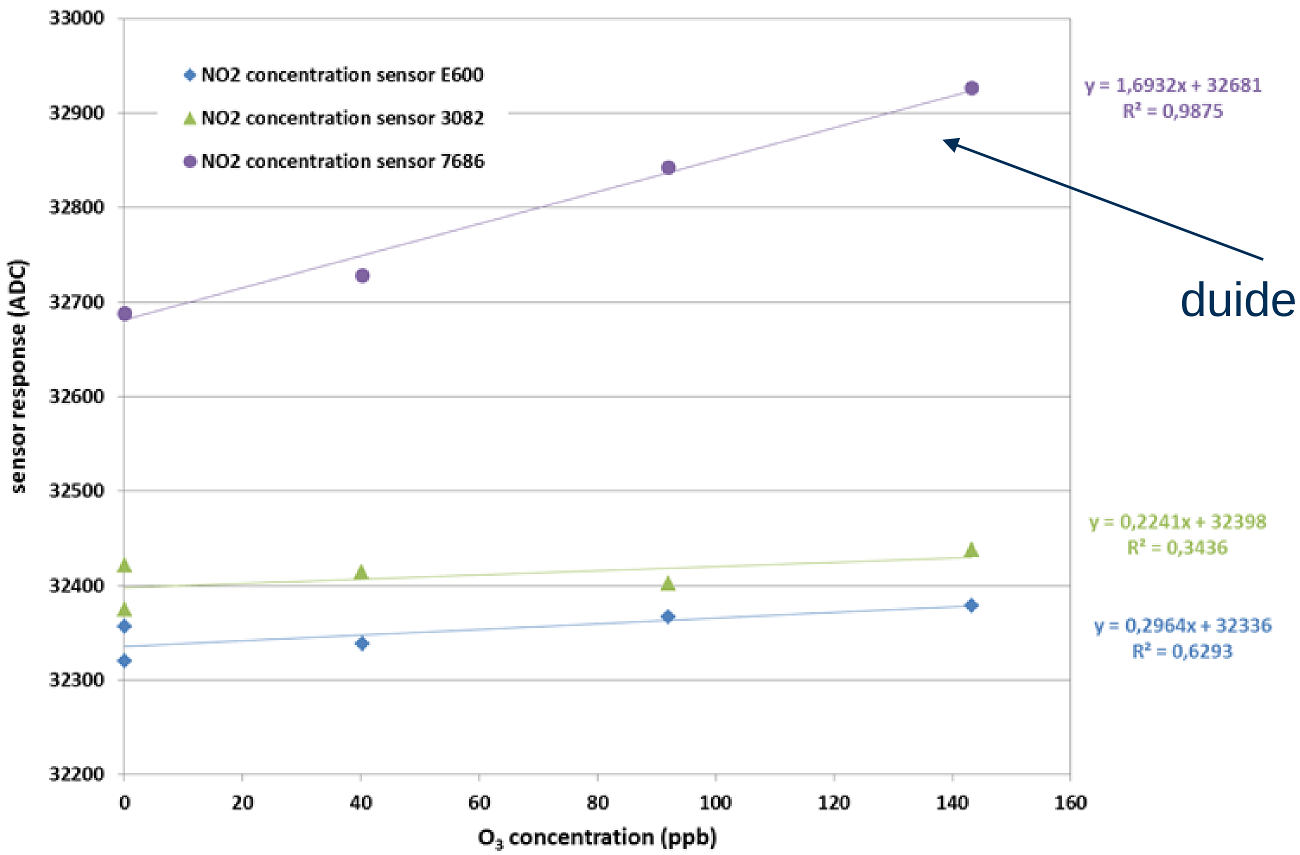


Interference of O_3 on NO_2 sensor



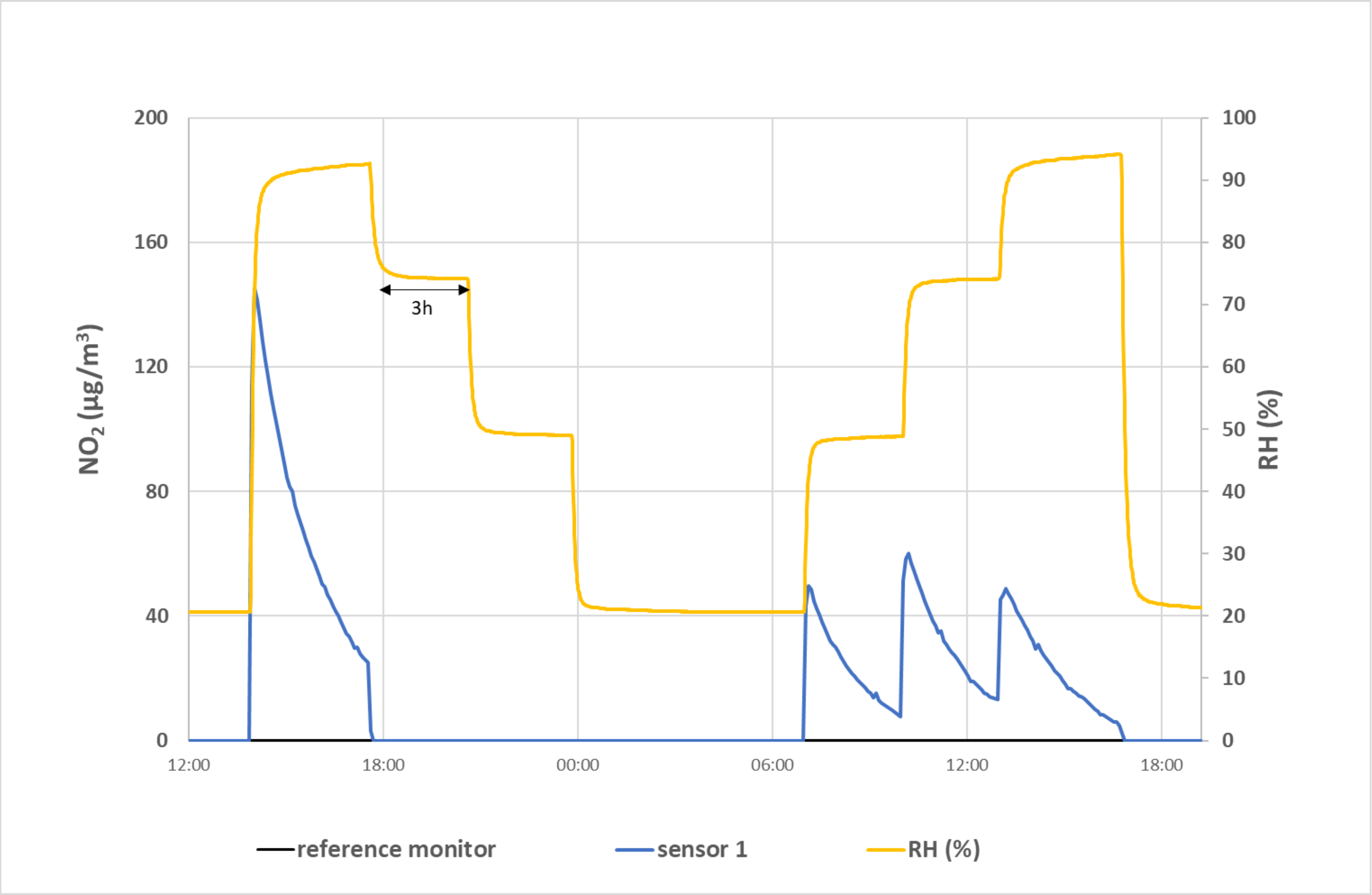
u(int) = 2.68 µg/m^3

Interference of O_3 on NO_2 sensor



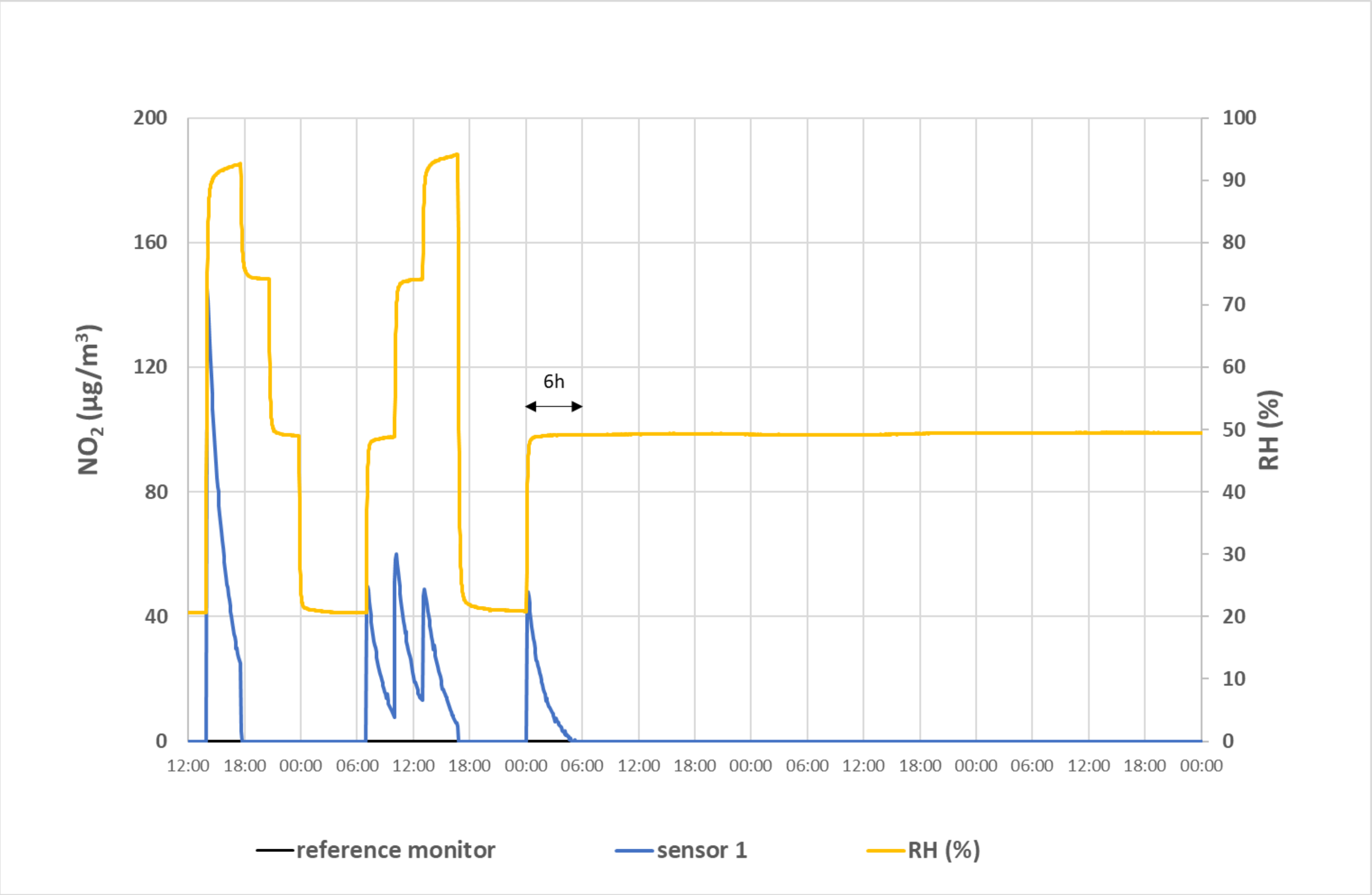
duidelijk interferentie van O_3

RH test @ zero



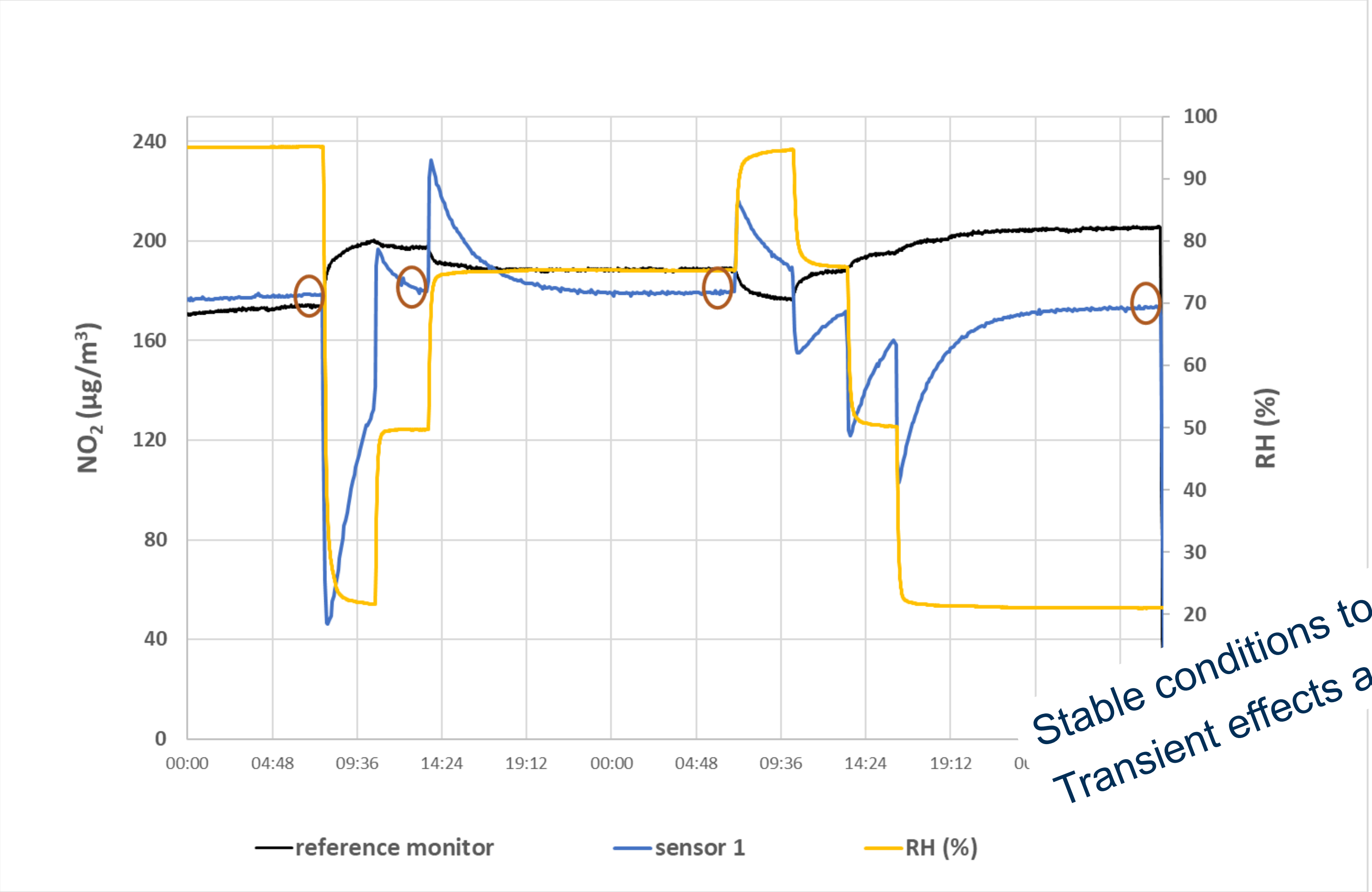
200
160
120
80
40
0
100
90
80
70
60
50
40
30
20
10
0
NO2 (µg/m3)
RH (%)
3h
12:00
18:00
00:00
06:00
12:00
18:00
reference monitor
sensor 1
RH (%)

RH test @ zero



200
160
120
80
40
0
NO2 (µg/m3)
100
90
80
70
60
50
40
30
20
10
0
RH (%)
6h
12:00 18:00 00:00 06:00 12:00 18:00 00:00 06:00 12:00 18:00 00:00 06:00 12:00 18:00 00:00 06:00 12:00 18:00 00:00
reference monitor
sensor 1
RH (%)

RH test @ 200 µg/m³



Stable conditions to assess RH effect
Transient effects are also important

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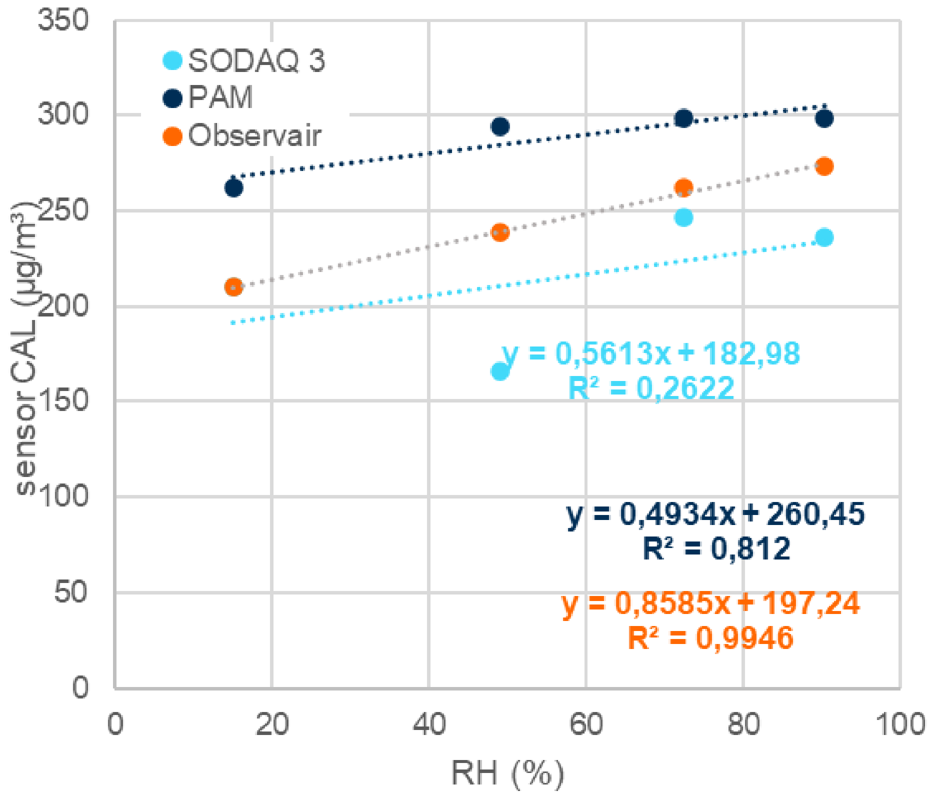
RH effect


350
300
250
200
150
100
50
0
sensor CAL (µg/m³)
SODAQ 3
PAM
Observair
y = 0,5613x + 182,98
R² = 0,2622
y = 0,4934x + 260,45
R² = 0,812
y = 0,8585x + 197,24
R² = 0,9946
0
20
40
60
80
100
RH (%)

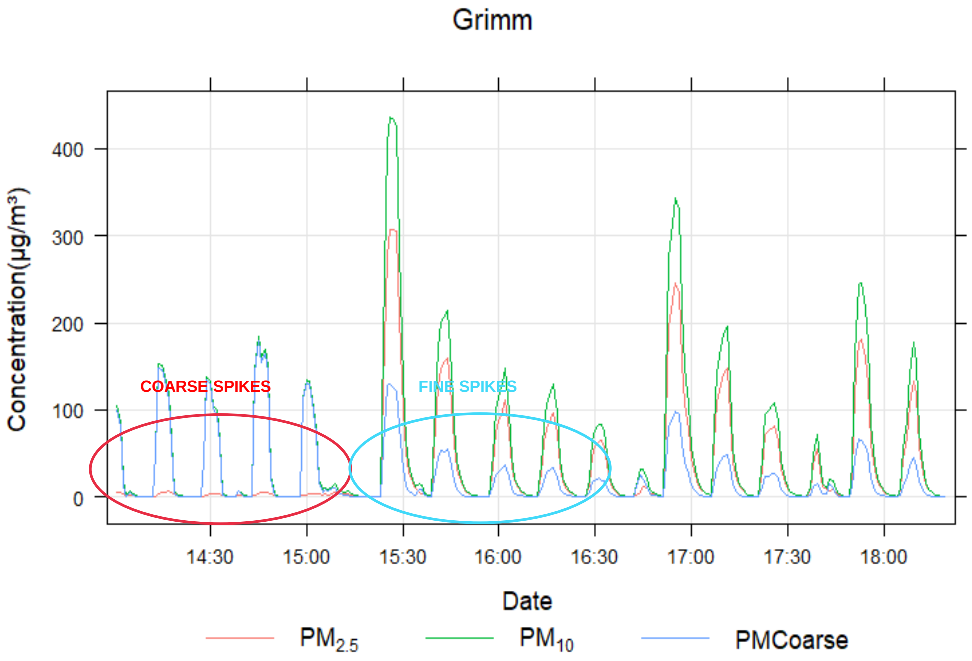
PM coarse test

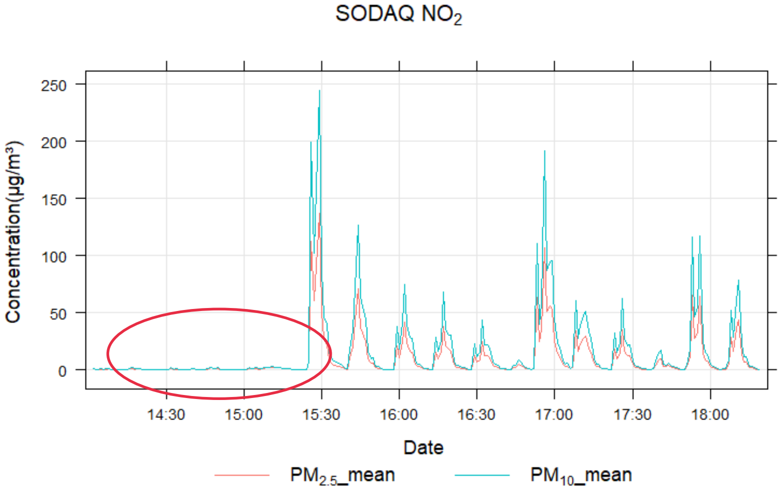
- $PM_{coarse} = PM_{10} - PM_{2.5}$

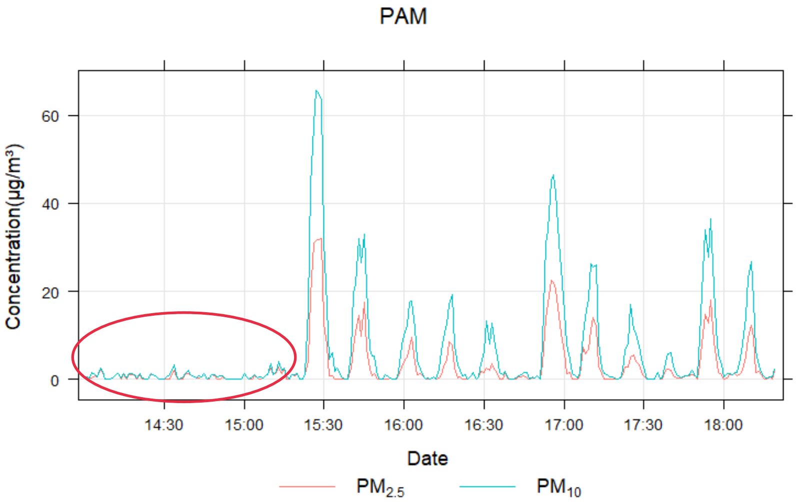
- Set-up:
  - Simulate high PM_{coarse} conditions in the lab
  - Expose sensor to very high and very low PM_{coarse} fractions

- Evaluation:
  - Compare sensor/reference at high and low PM_{coarse} conditions

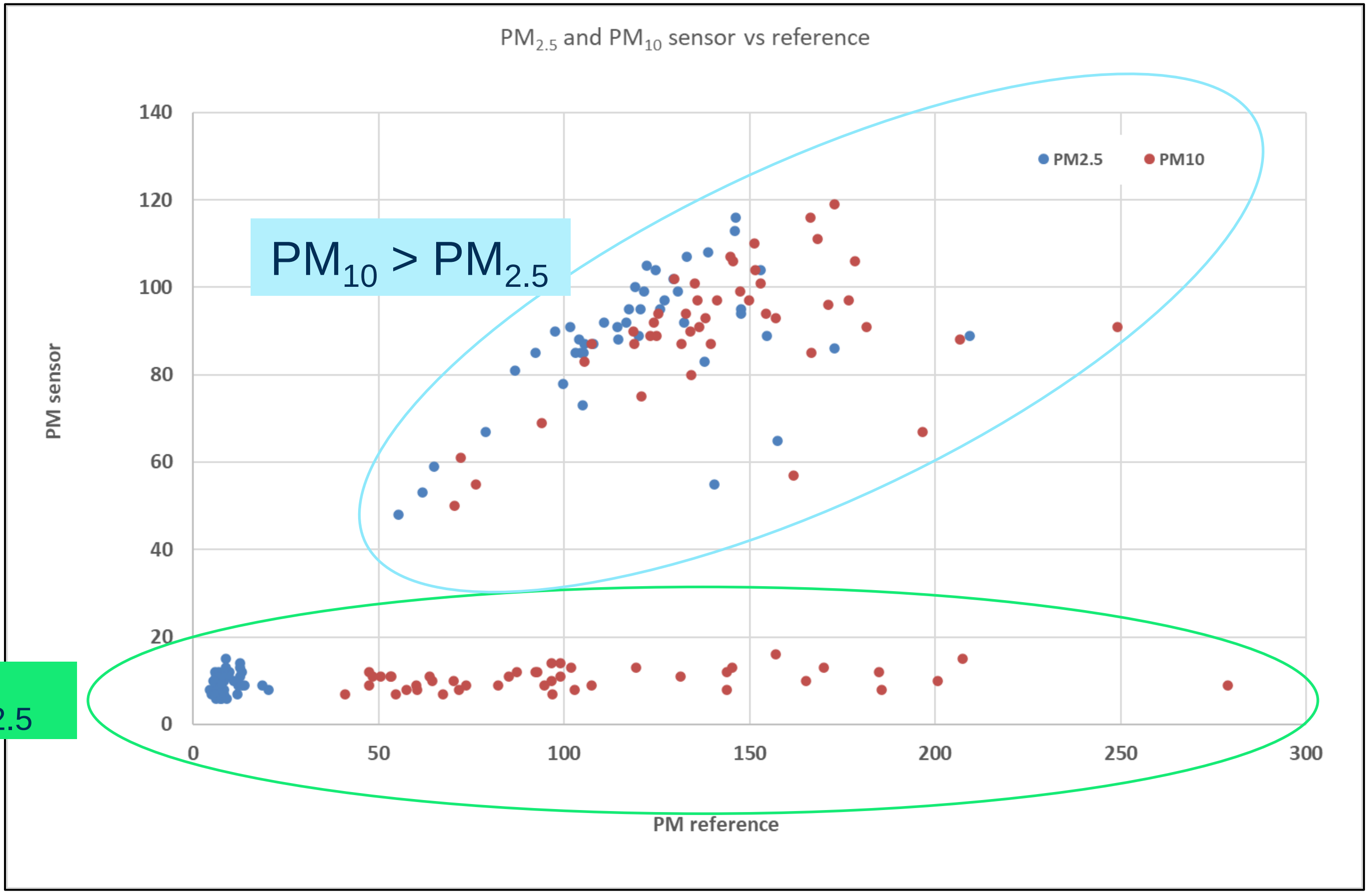
PM_{coarse} test







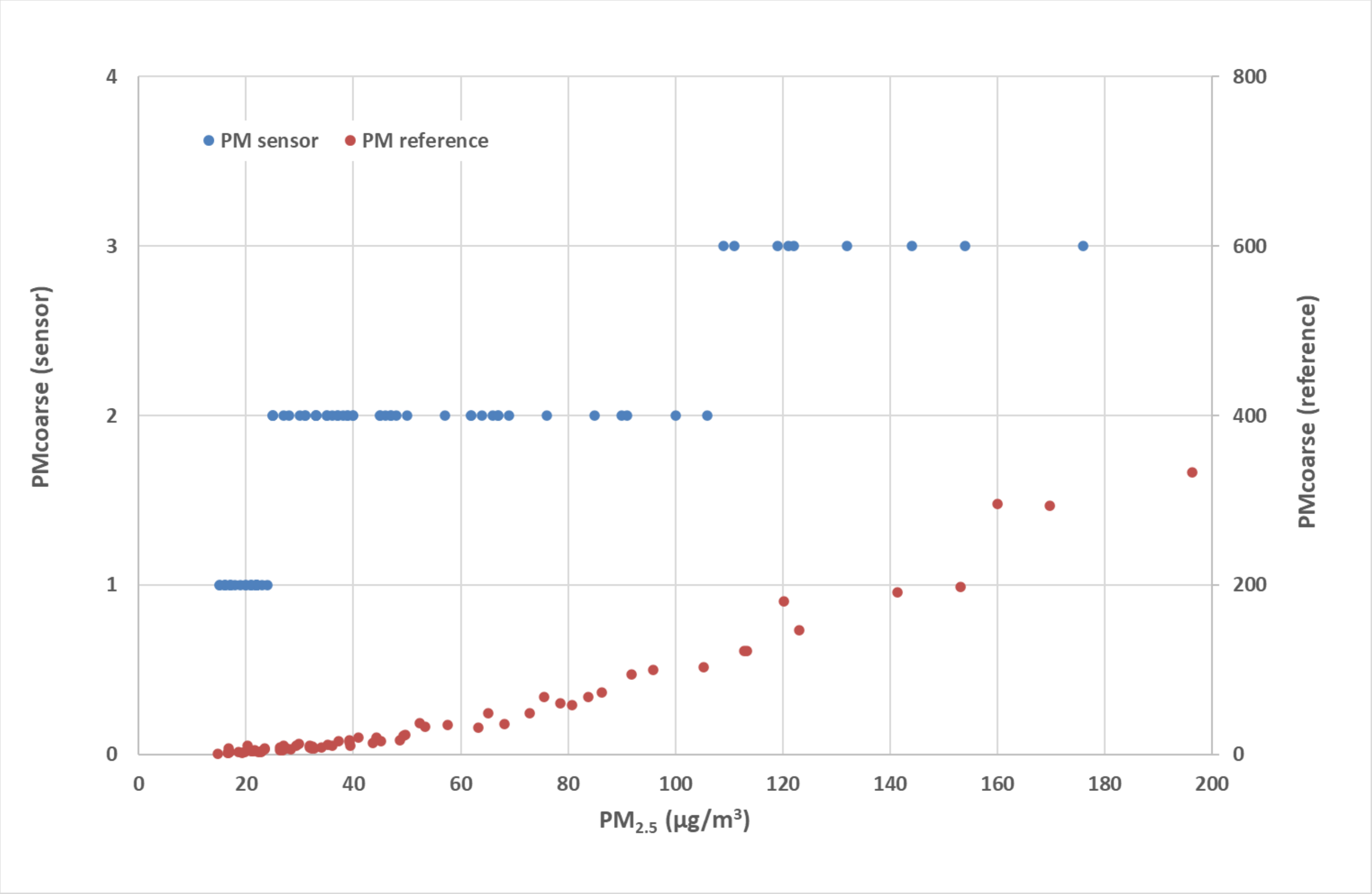
PM_{coarse} test



$PM_{10} > PM_{2.5}$

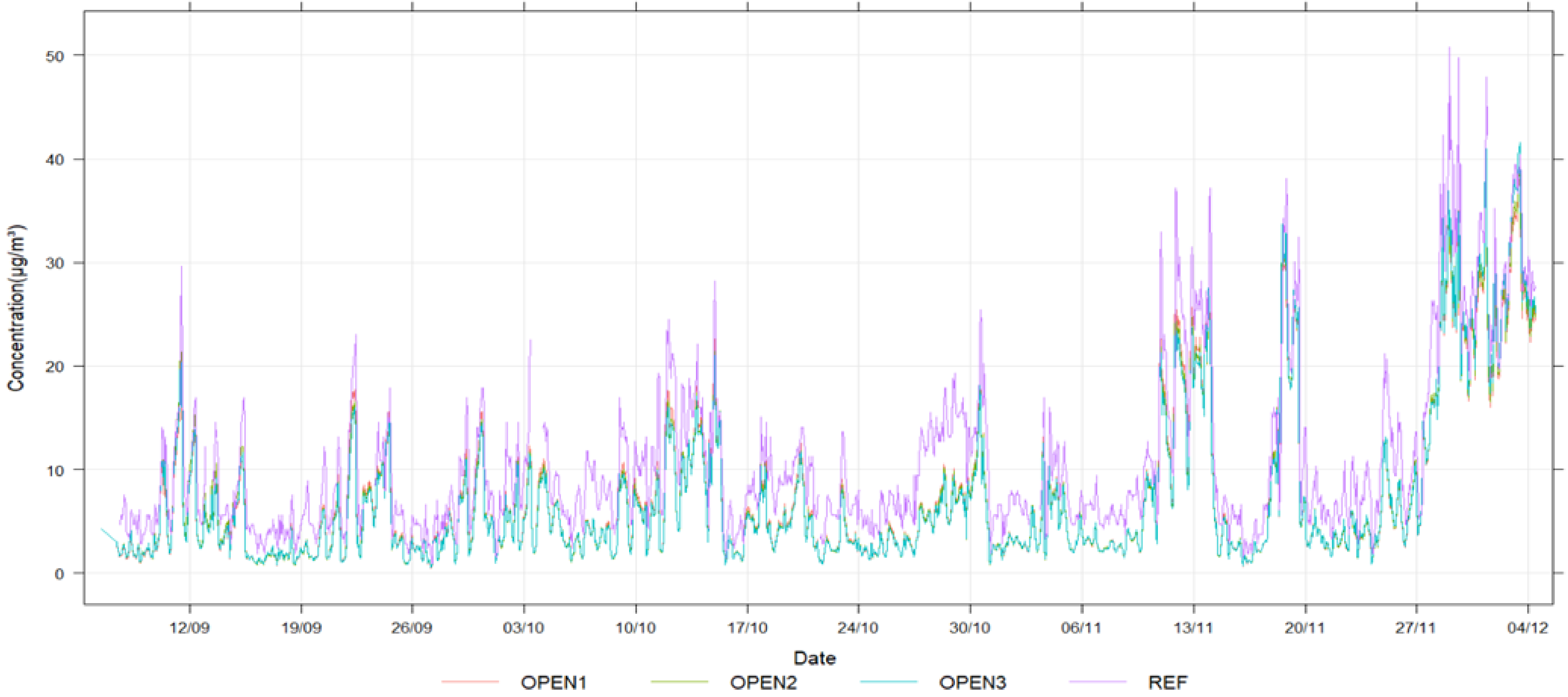
$PM_{10} >>>>> PM_{2.5}$

PM_{coarse} test



with dolomite dust

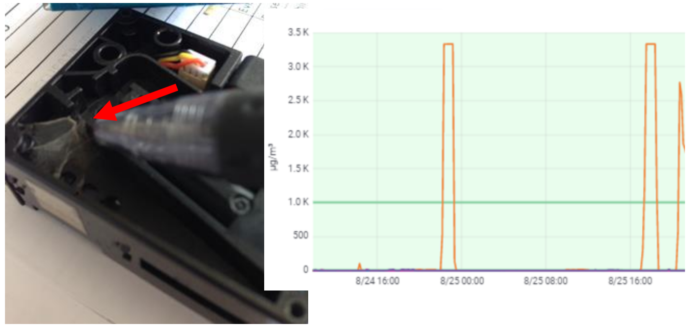
Between-sensor-uncertainty (field)

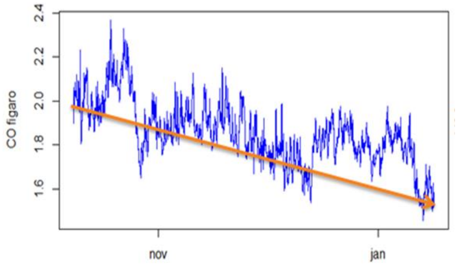


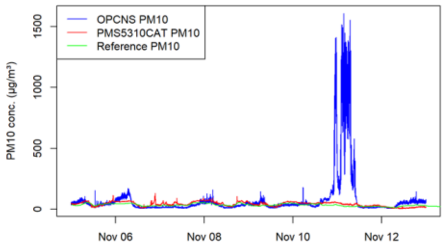
On-going quality control

- Need for on-going data quality control
  - Drift of sensor signal
  - Contamination of sensor
  - Interferences (not in calibration model)
  - Sensor failure

- How?
  - Setting thresholds
  - Comparison with nearby sensors
  - Baseline check
  - Re-calibration or control of calibration
  - Co-location of sensor with reference







Concluding remarks

- CEN TS (test protocol and classification) exists for gas sensors and for PM sensors under development
  - Current TS is focused on use of sensors in regulatory context and individual sensors (not networks)
  - Initial evaluation (kind of ‘type approval’)

- Need for on-going validation and quality control!
  - Data quality is function of deterioration and environmental conditions

- Quality of sensor is function of sensor type/measurement principle, sensor system (incl calibration), individual sensor (inter sensor variability), environmental conditions,…

- Required data quality is function of application
  - Fit for purpose
  - Post data processing
  - Set-up

Thanks!

Questions?

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