# PERFORMANCE ANALYSIS OF LOW-COST GAS SENSORS FOR AIR QUALITY CONTROL

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European Commission

CSIC
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MACPoll

Joint Research Centre

# Fixed/indicative measurements: definition

‘fixed measurements’ measurements taken at fixed sites, to determine the levels in accordance with the relevant *Data Quality Objectives* (*DQO*);

‘indicative measurements’ measurements which meet *DQOs* that are less strict than those required for *fixed measurements*;

They are use to check at *Limit Values* for an *Averaging Time* (for ozone 60 ppb – mean of 8 *hourly values*)

*European DIRECTIVE 2008/50/EC on ambient air quality and cleaner air for Europe, art. 2*

# AQD: Data Quality Objectives (DQO)

| | $SO_2$, $NO_2$/NO/ NOx, CO | Benzene | $O_3$ |
|---|---|---|---|
| Uncertainty for **fixed measurements** | 15 % | 25 % | 15 % |
| Uncertainty for **indicative measurements** | **25 %** | **30 %** | **30 %** |

# Indicative methods: what for ?

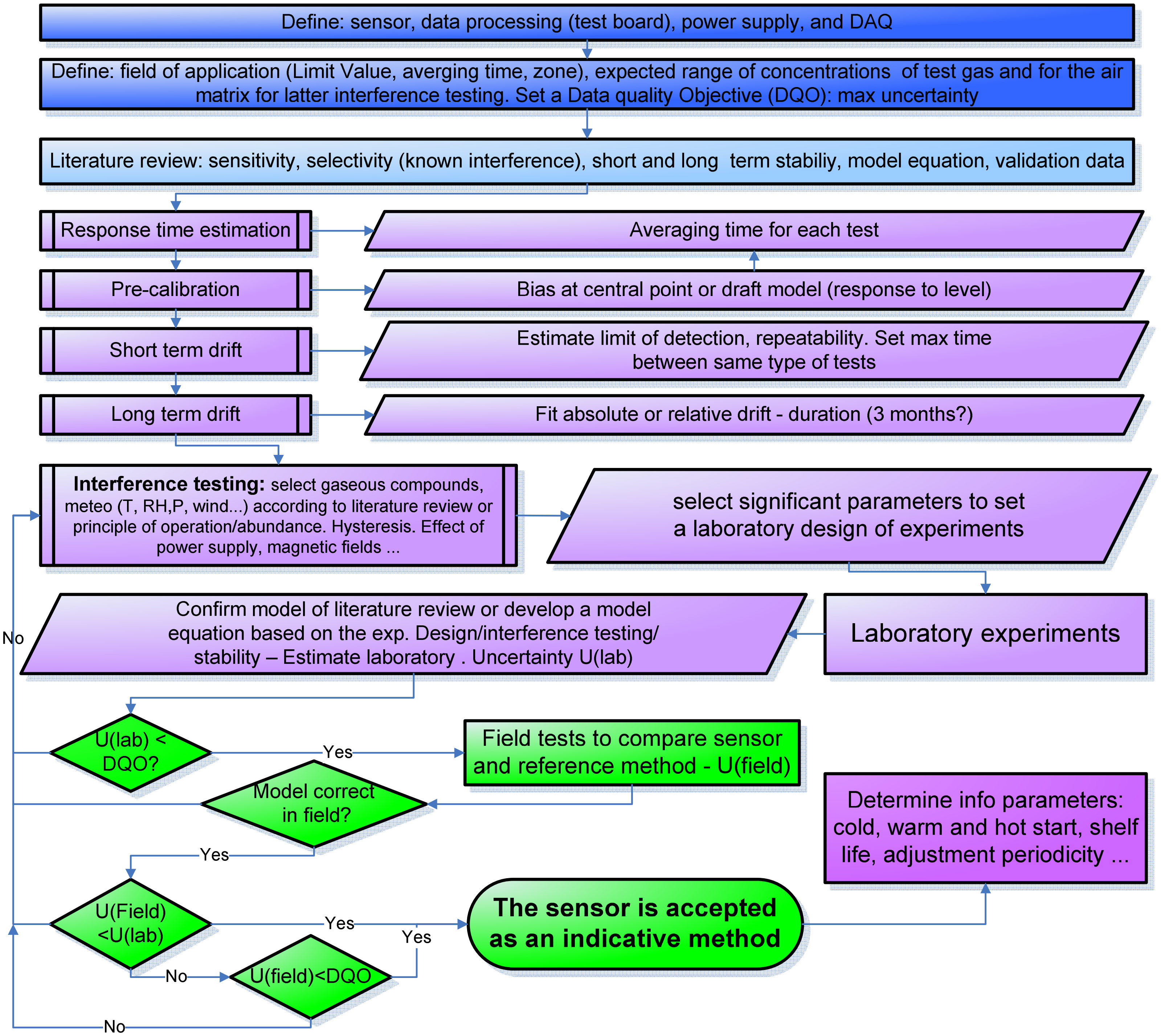
Fixed measurements are mandatory in zones and agglomerations where the upper assessment thresholds are exceeded, otherwise indicative methods can be used.
The use of indicative measurements allows for reduction of 50 % of the required minimum number of fixed sampling points.

*European DIRECTIVE 2008/50/EC on ambient air quality and cleaner air for Europe, art. 6*

# An indicative method:

Only parameter needed to demonstrate that a method is suitable as an indicative method is its measurement **uncertainty** …

However, to estimate the measurement uncertainty of micro-sensors, a huge quantity of metrological parameters has to be determined …


Define: sensor, data processing (test board), power supply, and DAQ
Define: field of application (Limit Value, averging time, zone), expected range of concentrations of test gas and for the air matrix for latter interference testing. Set a Data quality Objective (DQO): max uncertainty
Literature review: sensitivity, selectivity (known interference), short and long term stabiliy, model equation, validation data
Response time estimation
Averaging time for each test
Pre-calibration
Bias at central point or draft model (response to level)
Short term drift
Estimate limit of detection, repeatability. Set max time between same type of tests
Long term drift
Fit absolute or relative drift - duration (3 months?)
Interference testing: select gaseous compounds, meteo (T, RH,P, wind...) according to literature review or principle of operation/abundance. Hysteresis. Effect of power supply, magnetic fields ...
select significant parameters to set a laboratory design of experiments
Laboratory experiments
Confirm model of literature review or develop a model equation based on the exp. Design/interference testing/ stability – Estimate laboratory . Uncertainty U(lab)
No
U(lab) < DQO?
Yes
Field tests to compare sensor and reference method - U(field)
Model correct in field?
Yes
Determine info parameters: cold, warm and hot start, shelf life, adjustment periodicity ...
U(Field) <U(lab)
Yes
Yes
The sensor is accepted as an indicative method
No
U(field)<DQO
No

| | Tests | Temperature, °C | Relative humidity, % | Comment |
|---|---|---|---|---|
| 1 | Response Time | Mean | Mean | Three times: 0 to 80 % of Full Scale and 80% of FS to 0 |
| 2 | Pre-calibration | Mean | Mean | At least 3 levels including 0, LV, IT, AT, CL, LAT and UAT |
| 3-1 | Repeatability | Mean | Mean | 0 and 90 % of LV, 3 repetitions every averaging time |
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| 4-1 | Air matrix | Mean | Mean | Filtered air, laboratory air and ambient air at 0 and LV |
| 4-2 | Gaseous interference | Mean | Mean | Test selected interferences at zero and average level in ambient air |
| 4-3 | Temperature | From mean-10 °C to mean+10 °C by step of 5 °C | Mean | At LV |
| 4-4 | Humidity | Mean | From mean-20% to mean+20% by step of 10% | At LV |
| 4-5 | Hysteresis | Mean | Mean | Increasing-decreasing-increasing concentration of the pre-calibration levels |
| 4-6 | Pressure | Mean | Mean | overpressure 10 mbar and under pressure 5 mbar |
| 4-7 | Power supply effect | Mean | Mean | At LV test under 210, 220 and 230 V |
| 4-8 | Wind velocity | Mean | Mean | from 1 to 5 m/s (needed?) |
| 4-1 | Lab experiments (model) | Mean-10°C, mean, mean -10°C | Mean-20%, mean, mean + 20 % | 0, LV, AT for each significant parameters: temperature and humidity (levels) and wind, pressure and interference (2 levels) |
| 4-2 | Field experiments | | | At an automatic station equipped with reference method of measurements |
| 5-1 | Cold start, warm start, hot start | Mean | Mean | At LV |

# 1 - Response time

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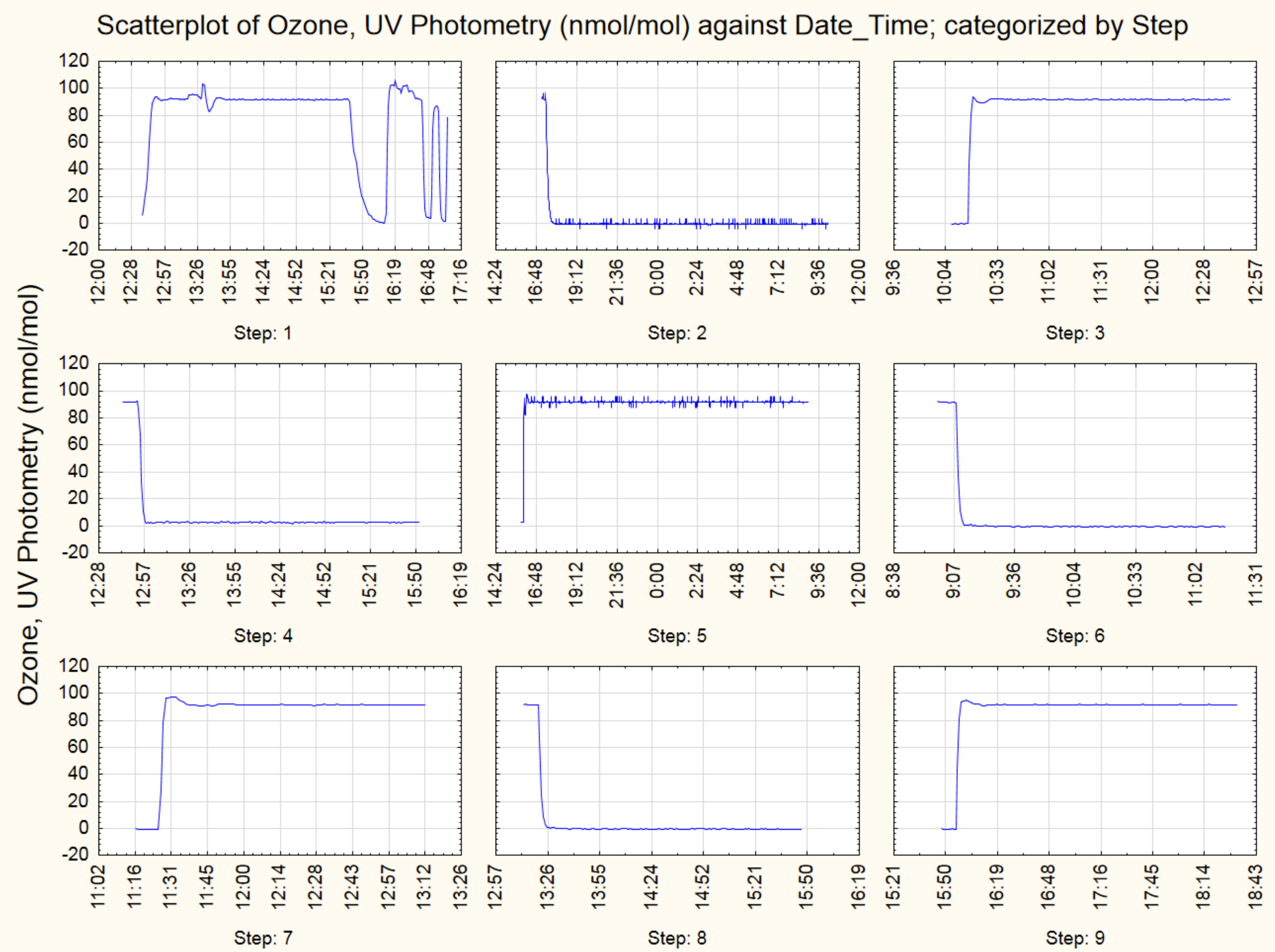

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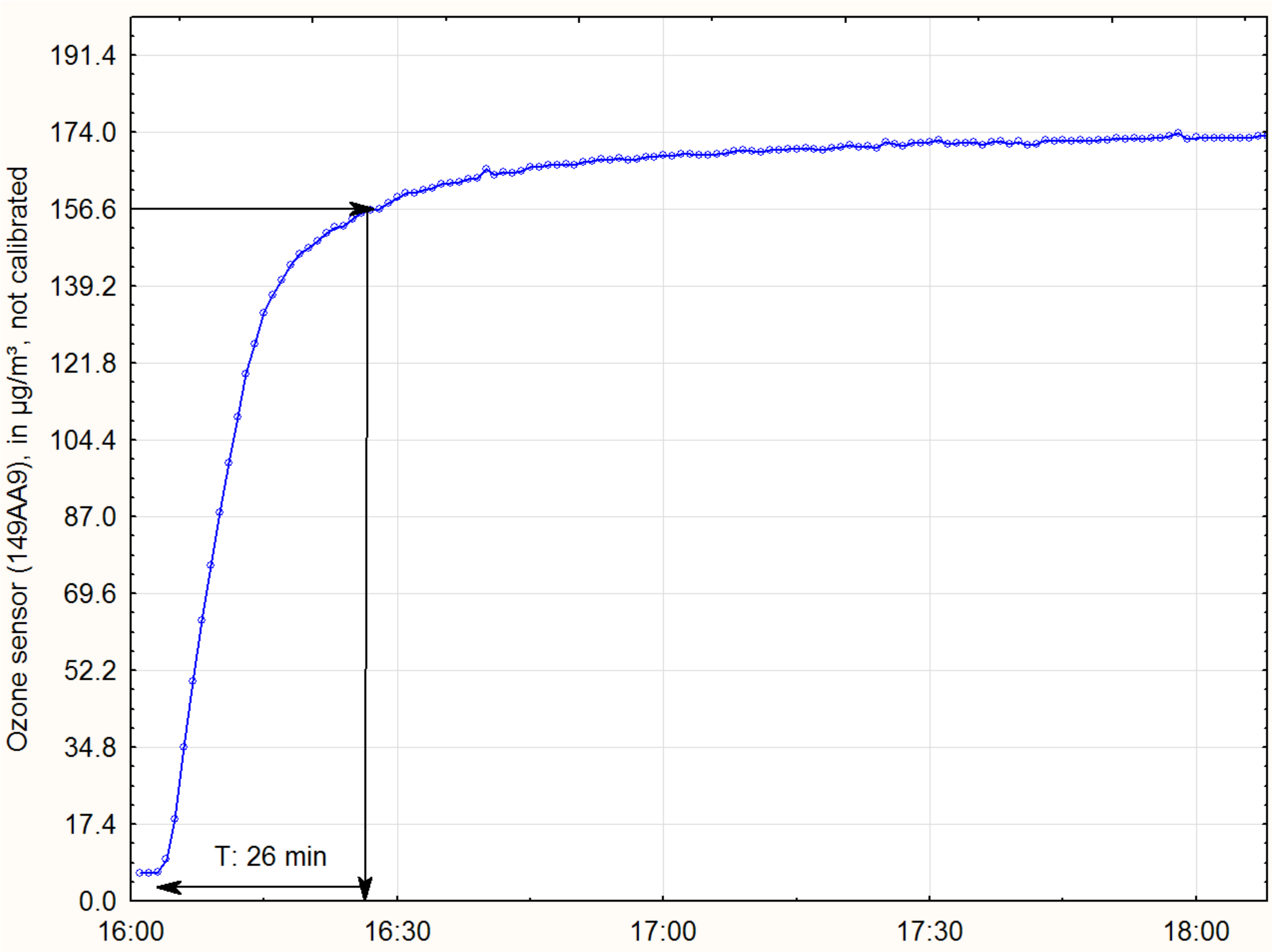

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# 1 - Response time

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| | Step 2 | Step 3 | Step 4 | Step 5 | Step 6 | Step 7 | Step 8 | Step 9 |
|---|---|---|---|---|---|---|---|---|
| $O_3$, nmol/mol | -0.6±0.2 | 91.7±0.2 | 2.6±0.3 | 91.7±0.2 | -0.5±0.2 | 91.7±0.3 | -0.5±0.2 | 91.±0.2 |
| $NO_2$, nmol/mol | 0.7±0.1 | 0.7±0.2 | 1.0±0.1 | 0.7±0.1 | 0.7±0.1 | 0.7±0.2 | 0.7±0.1 | 0.7±0.2 |
| NO, nmol/mol | 1.7±0.1 | 1.8±0.1 | 1.8±0.1 | 1.7±0.1 | 1.8±0.1 | 1.8±0.1 | 1.8±0.1 | 1.8±0.1 |
| Temperature, ℃ | 22.0±0.1 | 22.1±0.0 | 22.1±0.0 | 22.0±0.0 | 22.0±0.0 | 22.0 | 22.0 | 22.0 |
| Humidity, % | 57.7±0.7 | 60.0±0.0 | 59.9±0.1 | 60.0±0.0 | 60.0±0.0 | 60.0±0.1 | 60.0±0.2 | 60.0±0.0 |
| Pressure, kPa | 996±2 | 999±0.1 | 998±0.1 | 1000±0.3 | 1001±0.1 | 1000±0.2 | 999±0.4 | 998±0.1 |
| Time length | 900’ | 210’ | 210’ | 1050’ | 195’ | 180’ | 150’ | 165’ |

| | Step 2 | Step 3 | Step 4 long 90 | Step 5 | Step 6 | Step 7 | Step 8 | Step 9 |
|---|---|---|---|---|---|---|---|---|
| | Fall | Rise | Fall | Rise | Fall | Rise | Fall | Rise |
| $t_{90}$, O3 UV Photometry | 14 min | 4 min | 4 min | 5 min | 4 min | 4 min | 3 min | 3 min |
| $t_{90}$, CairClipO3 | 5 min | 3 min | 4 min | 4 min | 4min | 6 min | 4 min | 4 min |
| Response time, 4 x $t_{90}$ | 20 min | 12min | 16 min | 16 min | 16 min | 24 min | 16 min | 16 min |

# 1 Response time

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| | Rise Time (n=3) | Fall Time (n=3) | Average Time | Response time per type |
|---|---|---|---|---|
| Chamber – UV analyser (**substracted**) | 3 ‘ | 5 ‘ | 4 ‘ | |
| Unitec, Sens3000 (n =2) | 47 ' | 75 ' | 61 ' | |
| e2V, MICS-2610 (n =2) | 1 ' | 12 ' | 6 ' | |
| FIS, SP-61(n =2) | 57 ' | 54 ' | 56 ' | |
| Ingenieros Assessores, NanoEnvi (n =1) | 8 ' | 14 ' | 11 ' | 31 ' |
| e2v, OMC3 (n=2) | - | - | - | |
| e2v, OMC2 (n=2) | - | - | - | |
| e2v, MICS_Oz47 (n =7) | 19' | 27' | 23' | |
| IMN2P, WO3 (n =2) | 8' | 16' | 12' | 12 ' |
| Sensoric, O3E1F + Test Panel (n =1) | 1' | 2' | 2' | |
| Sensoric, O3E1 + 4-20mA Board (n =2) | 4 ' | 5 ' | 4 ' | **3 '** |
| αSense B4 (n =2) | 1 ' | 2 ' | 2 ' | |
| CairclipO3NO2 (n=1) | 3 ' | 3 ' | 3 ' | |
| Sensors’ Average response Time | 15' | 21 ' | 18 ' | |

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# 1 - Response time

- Response time < the averaging time of the Limit Value of the Directive (mean of hourly values over 8 hours). Duration of tests.
- Similar response time for rise and fall cycles?
- The sensor is fast enough for areas where air pollutants change fast (a few minutes) or for mobile measurements?

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# 2 Pre-calibration

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- Make sure that the transformation of sensor responses into gaseous concentrations does not include any bias at the mean temperature and relative humidity.

# 2 Pre-calibration

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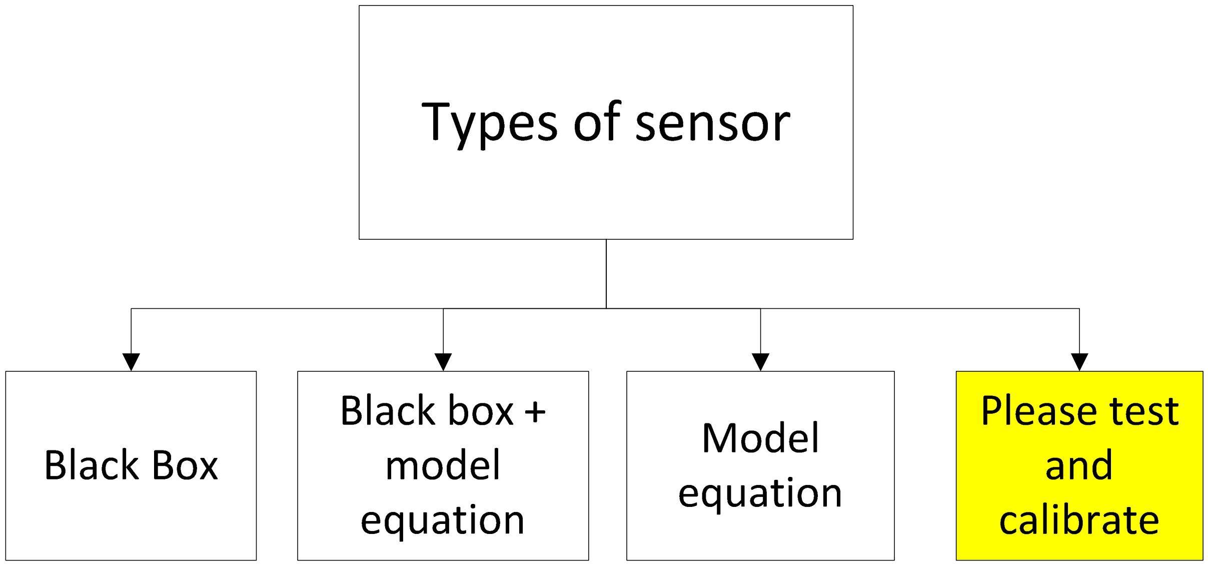

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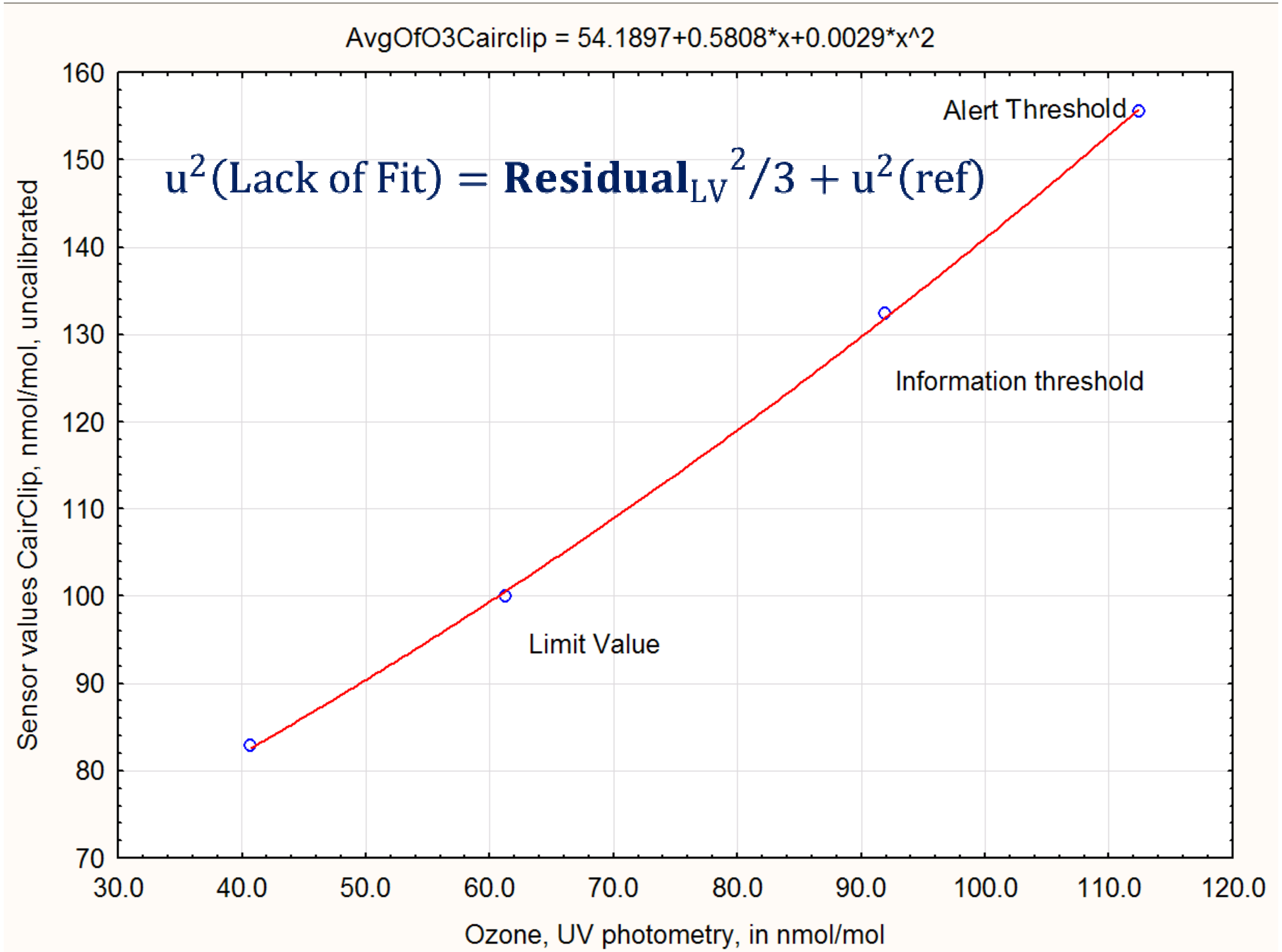

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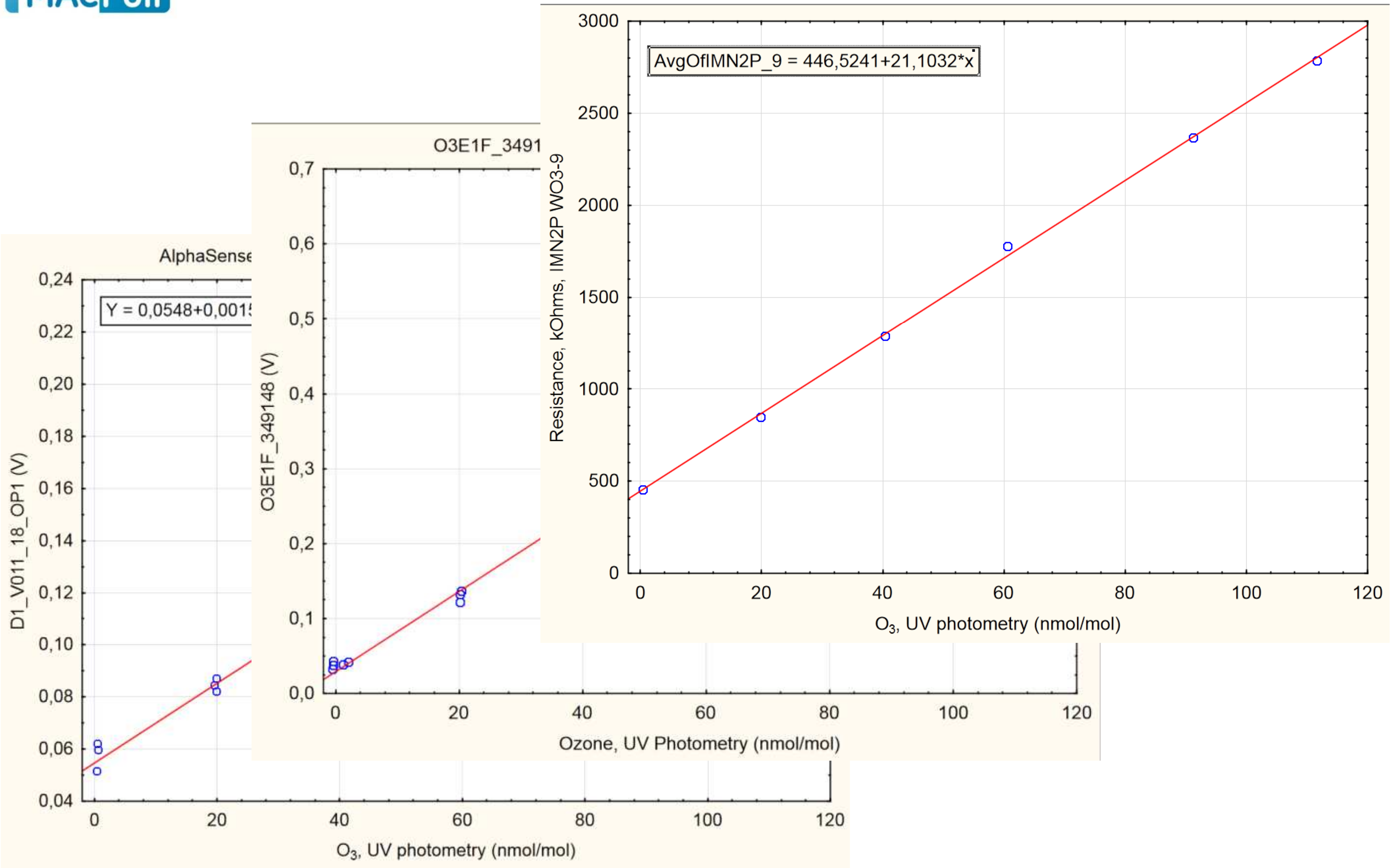

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| | Cold start, warm start, hot | | | |

# 3.1 Repeatability (hourly values)

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| | O3 | NO2 | NO | CO | Temp | Humidity | Pressure | CairClipO3 |
|---|---|---|---|---|---|---|---|---|
| | ppb | ppb | ppb | ppb | °C | % | hPa | ppb |
| Mean ± s (n=9) | 0,6 ± 0.1 | 0,7 ± 0.0 | 1,7 ± 0.1 | 250,2 ± 13 | 22,0 ± 0,0 | 59,0 ± 0,9 | 994,3 ± 3,9 | 38.2 ± 2.9 |
| Mean ± s (n=13) | 91,7 ± 0.0 | 0,7 ± 0.0 | 1,7 ± 0.0 | 268,2 ± 13 | 22,0 ± 0.0 | 60,0 ± 0.0 | 1000,3 ± 0,5 | 90.0 ±0.6 |

- **Repeatability: 1.6 ppb ($2\sqrt{2}s$ at 90 ppb of O3) possible difference between two hourly values :.**
- **Limit of detection: 5.8 ppb (3s of O3 at 0 ppb)**
- **Limit of quantification: 29 ppb (3s of O3 at 0 ppb).**
- **Sensor artificially blocked at minimum at about 40 ppb. Limits of detection and limit of quantification overestimated**

10

| | Tests | Temperature, °C | Relative humidity, % | Comment |
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# 3.2 Short term stability

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## hourly averages after 1 day drift

$$D_s = \frac{\sum_{After} R_s}{n} - \frac{\sum_{Before} R_s}{n}$$

$$D_s(\%) = \left| 1 - \frac{\sum_{After} R_s}{\sum_{Before} R_s} \right|$$

# 1 day drift for hourly averages at 0,60 and 90 nmol/mol

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| | Ds0, nmol/mol (n~19) | Ds60, nmol/mol-% (n~8) | Ds90, nmol/mol-% (n~6) |
|---|---|---|---|
| Res 1 (n =2) | 5.4 | 3.1 – 1.9 % | 2.7 – 2 % |
| Res 2 (n =2) | On going data treatment | | |
| Res 3 (n =2) | 13 | 15 – 9.5 % | 15 – 8.9 % |
| Res 4 (n =2) | 1.8 | 2.3 – 3.6 % | 2.1 – 2.6 % |
| Res 5 (n=2) | On going data treatment | | |
| Res 6 (n=2) | On going data treatment | | |
| Res 7 (n =1) | 1.9 | 2.9 – 2.5 % | 2.8 – 2.0 % |
| Res 8 (n =2) | 1.0 | 2.0 – 2.4 % | 4.6 – 4.4 % |
| Chem 1 (n =1) | 1.3 | 1.2 – 1.8 % | 1.2 – 1.1 % |
| Chem 2 (n =2) | Malfunction | Malfunction | Malfunction |
| Chem 3 (n = 2) | 4.4 | 1.4 – 0.9 % | 0.9 – 0.5 % |
| Chem 4 (n=1) | 4.7 | 1.0 – 2.5 % | 1.5 – 1.6 % |

| | Tests | Temperature, °C | Relative humidity, % | Comment |
|---|---|---|---|---|
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| 5-1 | Cold start, warm start, hot start | Mean | Mean | At LV |

# 3.3 Long term stability! 150 days

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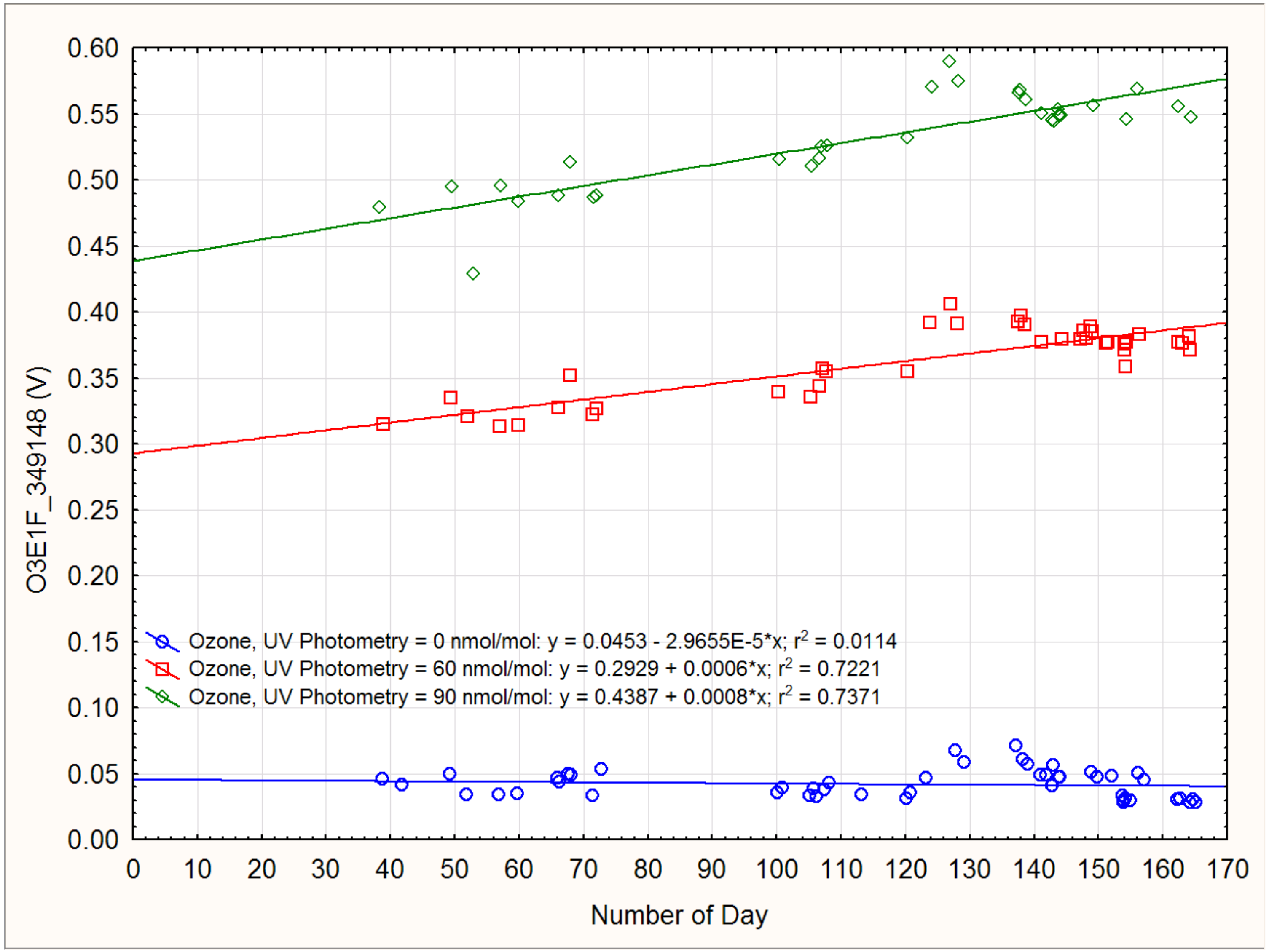


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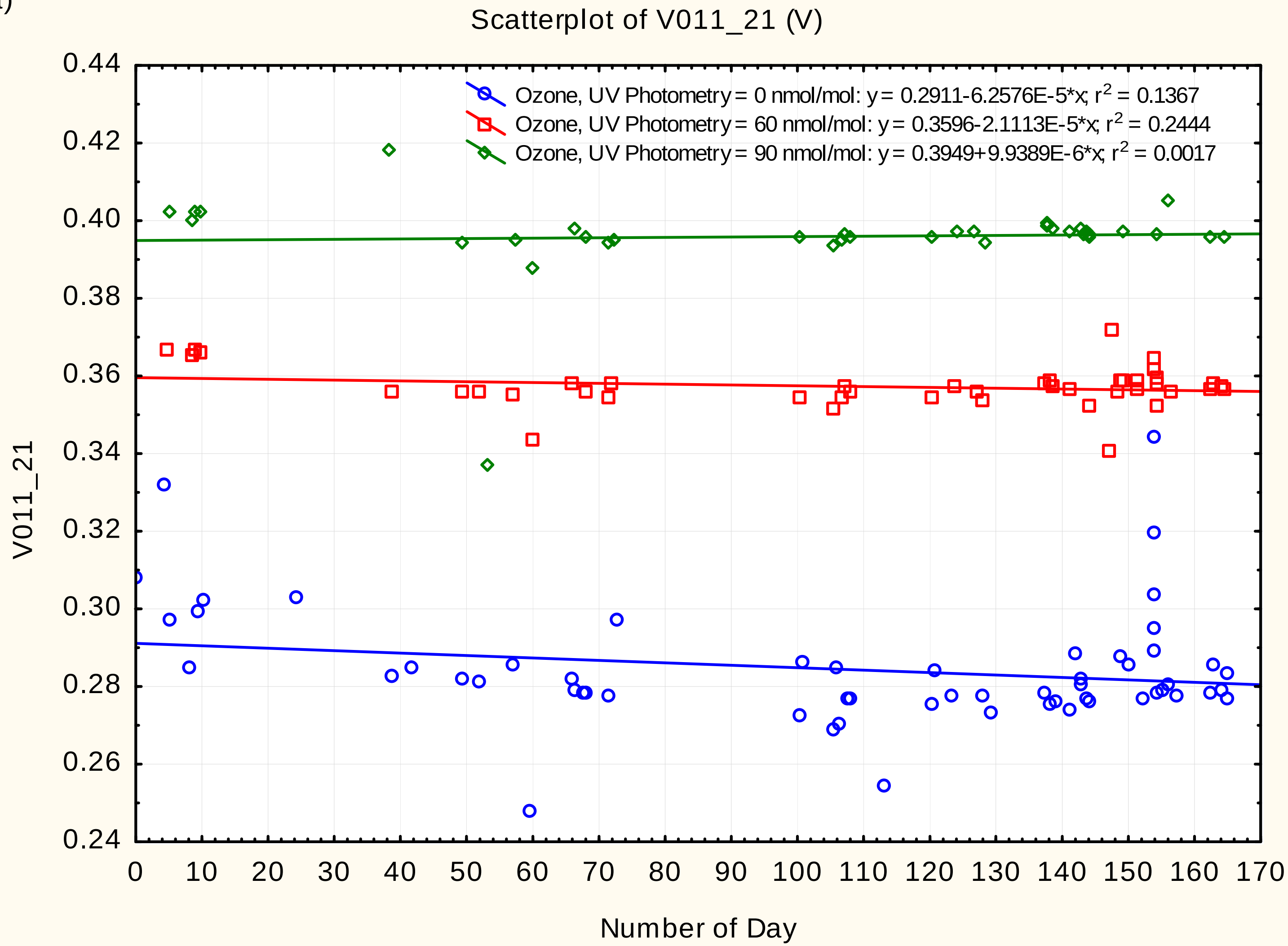
a)

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# 3.3 Long term stability

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- Identify trends in the long-term stability plots
- Decide if a correction can be added in the sensor model equation
- Estimate u(D_ls ), the contribution to the lab uncertainty: drift + noise (lack of fit)
- Set a periodicity of re-calibration of the sensor (a way to decrease the drift over time)
- Shall be used to correct the drift of sensors in the test results of this protocol

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# 3.2 Stability 150 days, hourly averages at 0, 60 and 90 ppb

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| | Regression line | | |
|---|---|---|---|
| | **Ds0, nmol/mol/100day** | **Ds60, nmol/mol/100day** | **Ds90, nmol/mol/100day** |
| Res 1 (n =2) | 3 | 9 – 15 % | 13 – 15 % |
| Res 2 (n =2) | On going data treatment | | |
| Res 3 (n =2) | 3 | 29 – 50 % | 34 – 35 % |
| Res 4 (n =2) | 3 | 4 - 7 % | 5 - |
| Res 5 (n=2) | On going data treatment | | |
| Res 6 (n=2) | On going data treatment | | |
| Res 7 (n =1) | On going data treatment | | |
| Res 8 (n =2) | On going data treatment | | |
| Chem 1 (n =1) | -1 | 11 – 20 % | 15 – 17 % |
| Chem 2 (n =2) | Malfunction | Malfunction | Malfunction |
| Chem 3 (n = 2) | -6 | -3 – 5 % | 1 – 1 % |
| Chem 4 (n=1) | On going data treatment | | |

**+ Noise**

| | Tests | Temperature, °C | Relative humidity, % | Comment |
|---|---|---|---|---|
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# 4.2 Gaseous interference $O_3$ sensors

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| Sensors/ | $NO_2$ | NO | CO | $CO_2$ | $NH_3$ |
|---|---|---|---|---|---|
| Interference, nmol/mol | 100 | 100 | 8000 | Purified air | ± 85 |
| O3, nmol/mol | 60 | 0 | 60 | 60 | 60 |
| RH (%)<br>T (ºC) | 60 %<br>22 ºC | 60 %<br>22 ºC | 60 %<br>22 ºC | 60 %<br>22 ºC | 60 %<br>22 ºC |
| Res 1 (n =2) | 14.1 % | -5.3 % | 9.8 % | -6.2 % | 6.0 % |
| Res 2 (n =2) | -3.3 % | - | 3.6 % | -0.1 % | -0.3 % |
| Res 3 (n =2) | 14.5 % | -10 % | 13.4 % | 5.0 % | 18 % |
| Res 4 (n =2) | 12.6 % | -1.6 % | -8.9 % | 1.0 % | 3.5 % |
| Res 5 (n=2) | - | - | - | - | - |
| Res 6 (n=2) | - | - | - | - | - |
| Res 7 (n =1) | - | - | - | - | - |
| Res 8 (n =2) | 1.2 % | -0.8 % | 0.1 % | -0.2 % | -1.9 % |
| Chem 1 (n =1) | 89.3 % | 1.3 % | -0.9 % | 0.2 % | 1.2 % |
| Chem 2 (n =2) | - | - | - | - | - |
| Chem 3 (n = 2) | 33.7 % | -7.7 % | -1.2 % | -0.4 % | 0.1 % |
| Chem 4 (n=1) | 107.7 % | -1.5 % | -2.4 % | 0.4 % | 2.3 % |

| | Tests | Temperature, °C | Relative humidity, % | Comment |
|---|---|---|---|---|
| 1 | Response Time | Mean | Mean | Three times: 0 to 80 % of Full Scale and 80% of FS to 0 |
| 2 | Pre-calibration | Mean | Mean | At least 3 levels including 0, LV, IT, AT, CL, LAT and UAT |
| 3-1 | Repeatability | Mean | Mean | 0 and 90 % of LV, 3 repetitions every averaging time |
| 3-2 | Short term drift | Mean | Mean | 0, 50 % and 80 % of LV, 3 repetitions every 24 hours |
| 3-3 | Long term drift | Mean | Mean | 0, 50 % and 80 % of LV, repeated every 2 weeks during 3 months |
| 4-1 | Air matrix | Mean | Mean | Filtered air, laboratory air and ambient air at 0 and LV |
| 4-2 | Gaseous interference | Mean | Mean | Test selected interferences at zero and average level in ambient air |
| 4-3 | Temperature | From mean-10 °C to mean+10 °C by step of 5 °C | Mean | At LV |
| 4-4 | Humidity | Mean | From mean-20% to mean+20% by step of 10% | At LV |
| 4-5 | Hysteresis | Mean | Mean | Increasing-decreasing-increasing concentration of the pre-calibration levels |
| 4-6 | Pressure | Mean | Mean | overpressure 10 mbar and under pressure 5 mbar |
| 4-7 | Power supply effect | Mean | Mean | At LV test under 210, 220 and 230 V |
| 4-8 | Wind velocity | Mean | Mean | from 1 to 5 m/s (needed?) |
| 4-1 | Lab experiments (model) | Mean-10°C, mean, mean -10°C | Mean-20%, mean, mean + 20 % | 0, LV, AT for each significant parameters: temperature and humidity (levels) and wind, pressure and interference (2 levels) |
| 4-2 | Field experiments | | | At an automatic station equipped with reference method of measurements |

# 4.3-4.4 Temperature humidity

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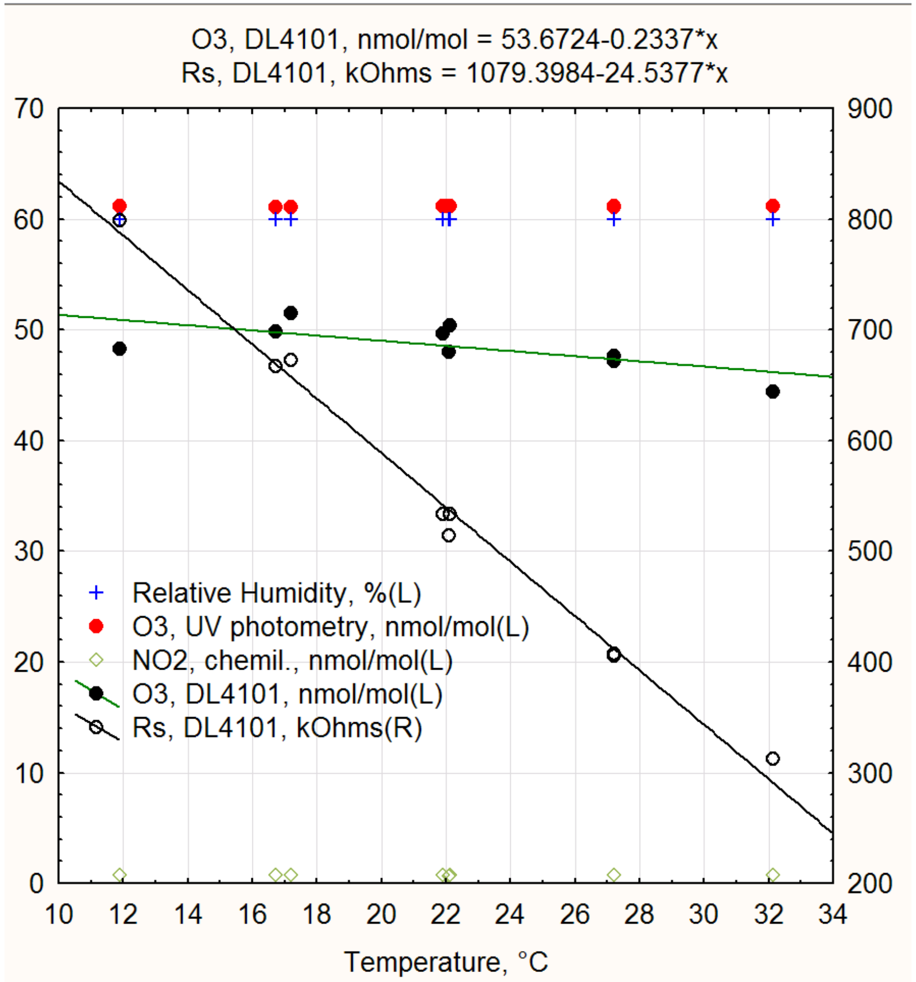


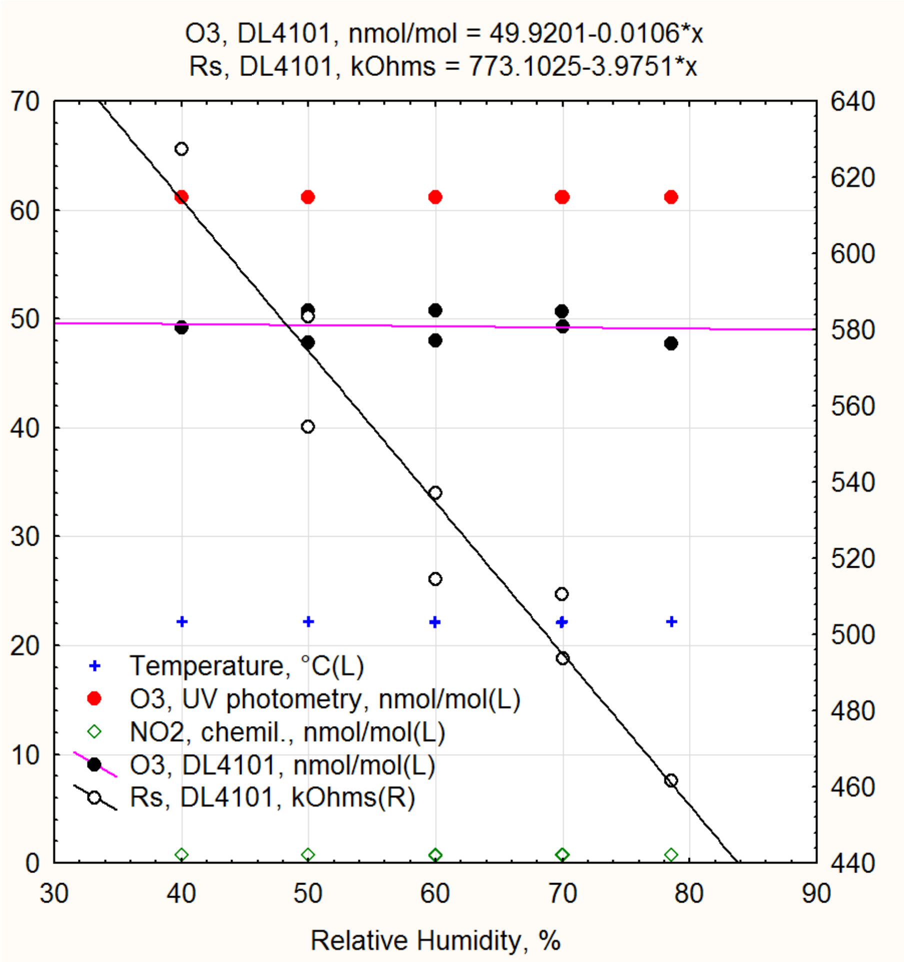

| | Tests | Temperature, °C | Relative humidity, % | Comment |
|---|---|---|---|---|
| 1 | Response Time | Mean | Mean | Three times: 0 to 80 % of Full Scale and 80% of FS to 0 |
| 2 | Pre-calibration | Mean | Mean | At least 3 levels including 0, LV, IT, AT, CL, LAT and UAT |
| 3-1 | Repeatability | Mean | Mean | 0 and 90 % of LV, 3 repetitions every averaging time |
| 3-2 | Short term drift | Mean | Mean | 0, 50 % and 80 % of LV, 3 repetitions every 24 hours |
| 3-3 | Long term drift | Mean | Mean | 0, 50 % and 80 % of LV, repeated every 2 weeks during 3 months |
| 4-1 | Air matrix | Mean | Mean | Filtered air, laboratory air and ambient air at 0 and LV |
| 4-2 | Gaseous interference | Mean | Mean | Test selected interferences at zero and average level in ambient air |
| 4-3 | Temperature | From mean-10 °C to mean+10 °C by step of 5 °C | Mean | At LV |
| 4-4 | Humidity | Mean | From mean-20% to mean+20% by step of 10% | At LV |
| 4-5 | Hysteresis | Mean | Mean | Increasing-decreasing-increasing concentration of the pre-calibration levels |
| 4-6 | Pressure | Mean | Mean | overpressure 10 mbar and under pressure 5 mbar |
| 4-7 | Power supply effect | Mean | Mean | At LV test under 210, 220 and 230 V |
| 4-8 | Wind velocity | Mean | Mean | from 1 to 5 m/s (needed?) |
| 4-1 | Lab experiments (model) | Mean-10°C, mean, mean -10°C | Mean-20%, mean, mean + 20 % | 0, LV, AT for each significant parameters: temperature and humidity (levels) and wind, pressure and interference (2 levels) |
| 4-2 | Field experiments | | | At an automatic station equipped with reference method of measurements |
| | Cold start, warm start, hot | | | |

# 4.5 Hysteresis

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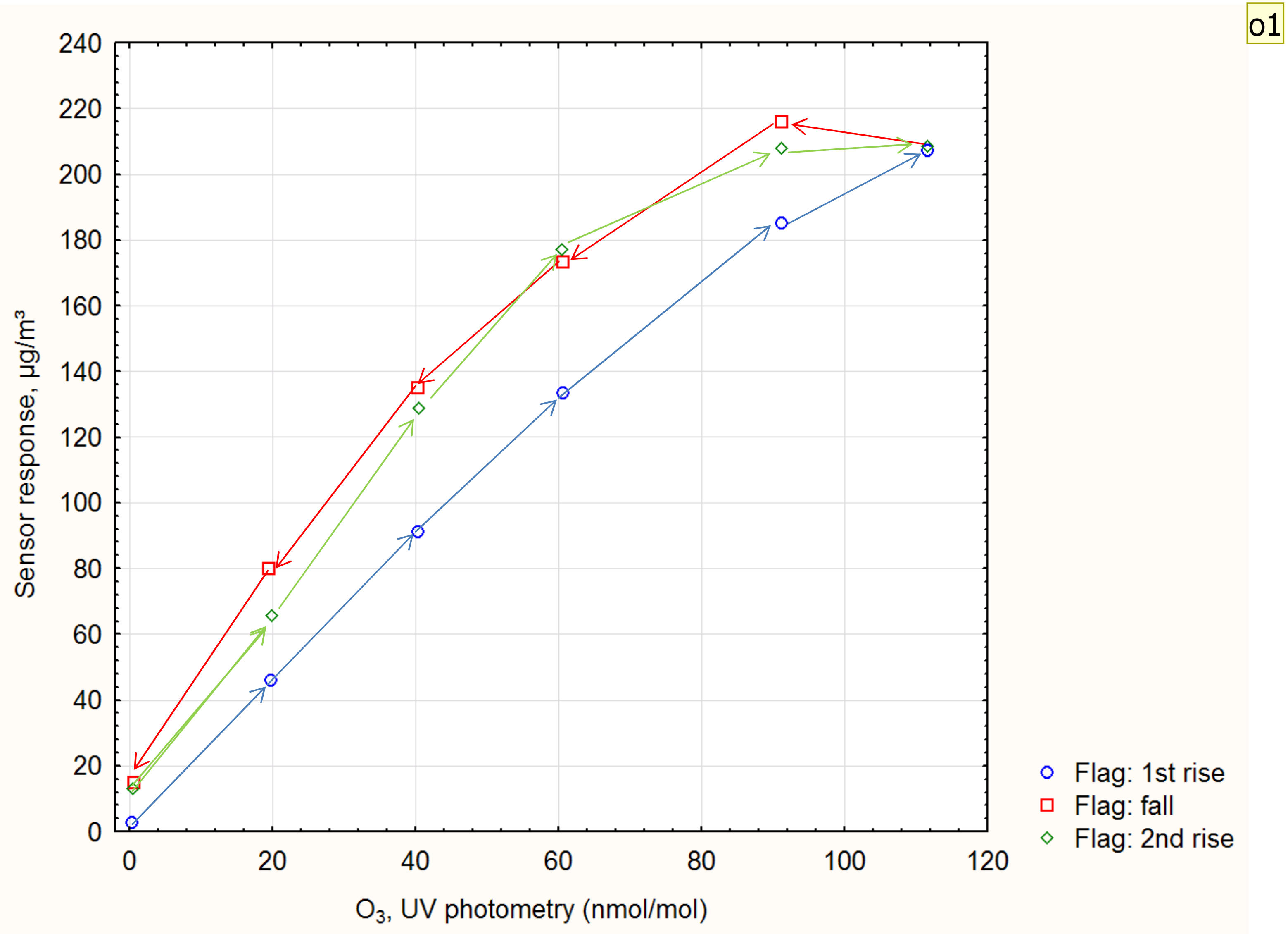

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# 4.5 Hysteresis

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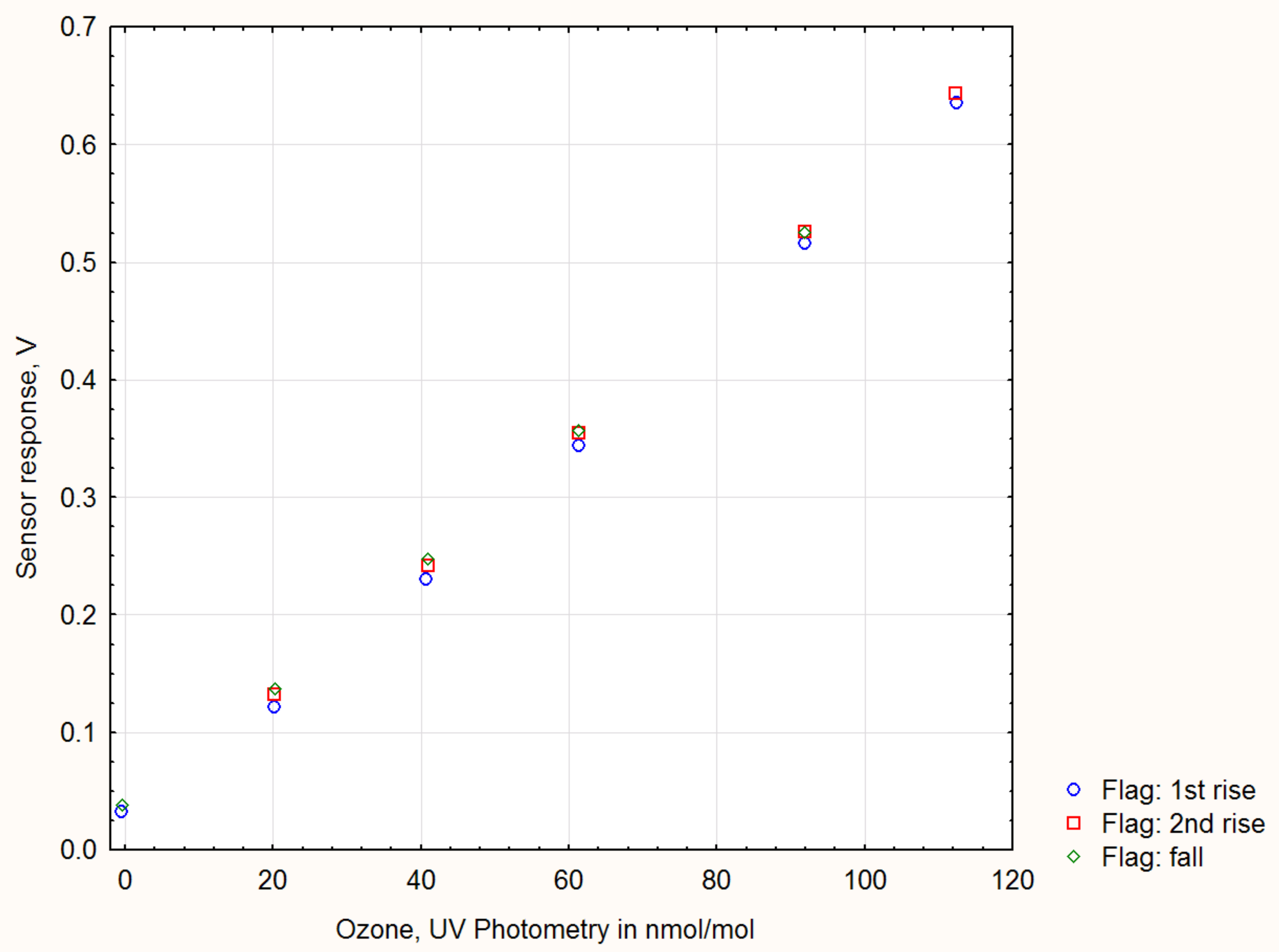

| | Tests | Temperature, °C | Relative humidity, % | Comment |
|---|---|---|---|---|
| 1 | Response Time | Mean | Mean | Three times: 0 to 80 % of Full Scale and 80% of FS to 0 |
| 2 | Pre-calibration | Mean | Mean | At least 3 levels including 0, LV, IT, AT, CL, LAT and UAT |
| 3-1 | Repeatability | Mean | Mean | 0 and 90 % of LV, 3 repetitions every averaging time |
| 3-2 | Short term drift | Mean | Mean | 0, 50 % and 80 % of LV, 3 repetitions every 24 hours |
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| 4-2 | Gaseous interference | Mean | Mean | Test selected interferences at zero and average level in ambient air |
| 4-3 | Temperature | From mean-10 °C to mean+10 °C by step of 5 °C | Mean | At LV |
| 4-4 | Humidity | Mean | From mean-20% to mean+20% by step of 10% | At LV |
| 4-5 | Hysteresis | Mean | Mean | Increasing-decreasing-increasing concentration of the pre-calibration levels |
| 4-6 | Pressure | Mean | Mean | overpressure 10 mbar and under pressure 5 mbar |
| 4-7 | Power supply effect | Mean | Mean | At LV test under 210, 220 and 230 V |
| 4-8 | Wind velocity | Mean | Mean | from 1 to 5 m/s (needed?) |
| 4-1 | Lab experiments (model) | Mean-10°C, mean, mean + 10°C | Mean-20%, mean, mean + 20 % | 0, LV, AT for each significant parameters: temperature and humidity (levels) and wind, pressure and interference (2 levels) |
| 4-2 | Field experiments | | | At an automatic station equipped with reference |

# 4.1 Experimental design

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| $O_3$ nmol/mol | $NO_2$ nmol/mol | Temp. | Rel. Hum. | Total |
|---|---|---|---|---|
| 0 | | | | |
| 20 | | | | |
| 40 | | | | |
| 60 | | 12 | 40 | |
| 90 | 0 | 22 | 60 | |
| 110 | 100 | 32 | 80 | |
| 6 levels | 2 levels | 3 levels | 3 levels | 108 trials |

# 4.1 Experimental design

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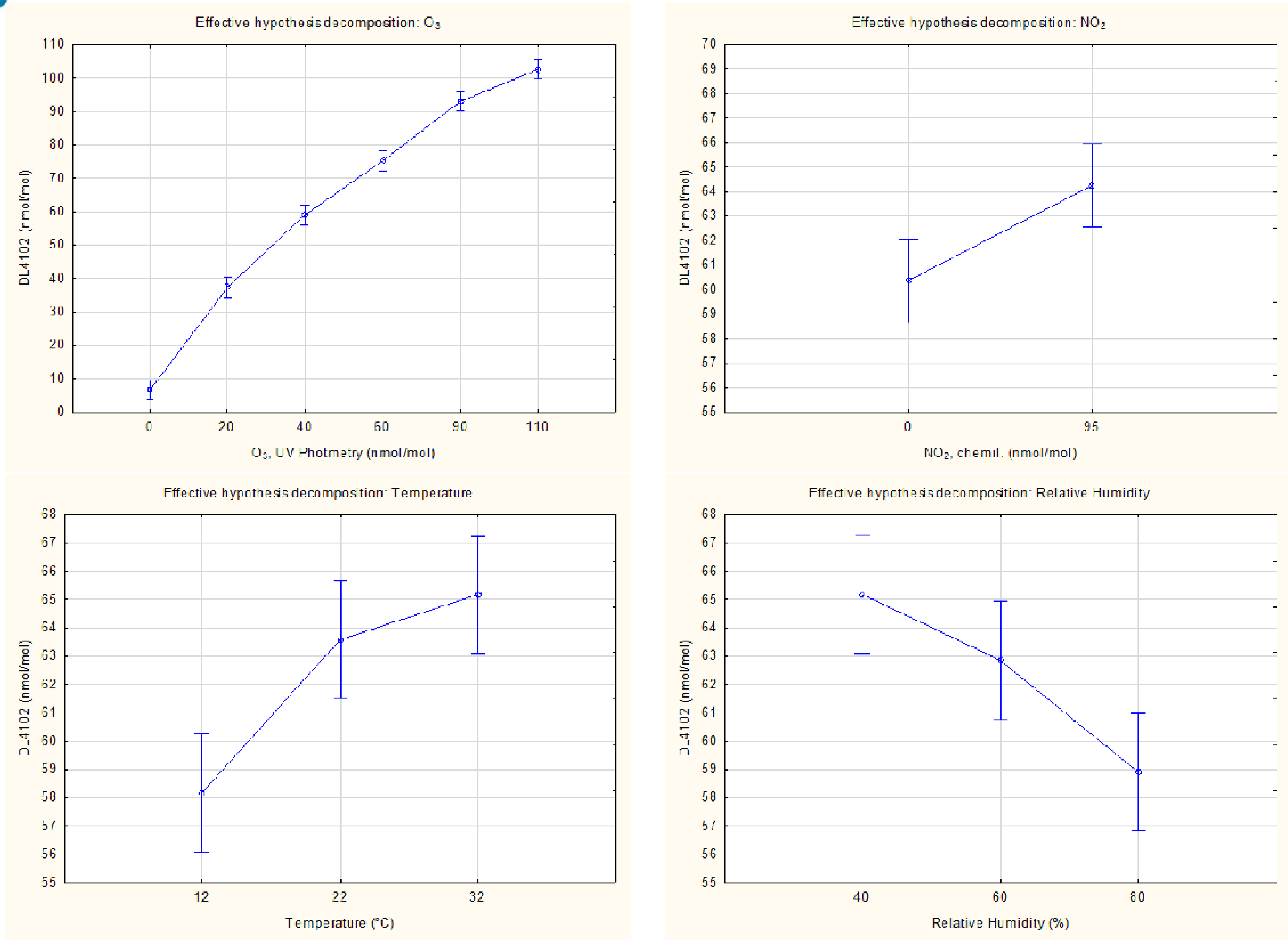


$$Sr_{DL4102} = 17.3_{\pm 4.5} + 0.84_{\pm 0.02} * O3 + 0.36_{\pm 0.11} * T - 0.16_{\pm 0.06} * RH + 0.039_{\pm 0.024} * NO2$$

# 4.1 Lab uncertainty

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Using the model equation developed with the desing of experiments design by application of the GUM method.

$$\boldsymbol{U}^2(O3) = \mathbf{2}.\sum\left(\frac{\partial O3}{\partial X_i}\right)^2 u^2(X_i)$$

Add in a quadratic way uncertainty of :

- long-term stability (with re-calibration)
- hysteresis (difficult to include in model equation)
- the interferences that were not included in the model and the ones that cannot be corrected in field

U < 30 %

| | Tests | Temperature, °C | Relative humidity, % | Comment |
|---|---|---|---|---|
| 1 | Response Time | Mean | Mean | Three times: 0 to 80 % of Full Scale and 80% of FS to 0 |
| 2 | Pre-calibration | Mean | Mean | At least 3 levels including 0, LV, IT, AT, CL, LAT and UAT |
| 3-1 | Repeatability | Mean | Mean | 0 and 90 % of LV, 3 repetitions every averaging time |
| 3-2 | Short term drift | Mean | Mean | 0, 50 % and 80 % of LV, 3 repetitions every 24 hours |
| 3-3 | Long term drift | Mean | Mean | 0, 50 % and 80 % of LV, repeated every 2 weeks during 3 months |
| 4-1 | Air matrix | Mean | Mean | Filtered air, laboratory air and ambient air at 0 and LV |
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| 4-3 | Temperature | From mean-10 °C to mean+10 °C by step of 5 °C | Mean | At LV |
| 4-4 | Humidity | Mean | From mean-20% to mean+20% by step of 10% | At LV |
| 4-5 | Hysteresis | Mean | Mean | Increasing-decreasing-increasing concentration of the pre-calibration levels |
| 4-6 | Pressure | Mean | Mean | overpressure 10 mbar and under pressure 5 mbar |
| 4-7 | Power supply effect | Mean | Mean | At LV test under 210, 220 and 230 V |
| 4-8 | Wind velocity | Mean | Mean | from 1 to 5 m/s (needed?) |
| 4-1 | Lab experiments (model) | Mean-10°C, mean, mean -10°C | Mean-20%, mean, mean + 20 % | 0, LV, AT for each significant parameters: temperature and humidity (levels) and wind, pressure and interference (2 levels) |
| 4-2 | Field experiments | | | At an automatic station equipped with reference method of measurements |
| 5-1 | Cold start, warm start, hot start | Mean | Mean | At LV |

# 4.2 Measurements on site

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# 4.2 Field tests, hourly values

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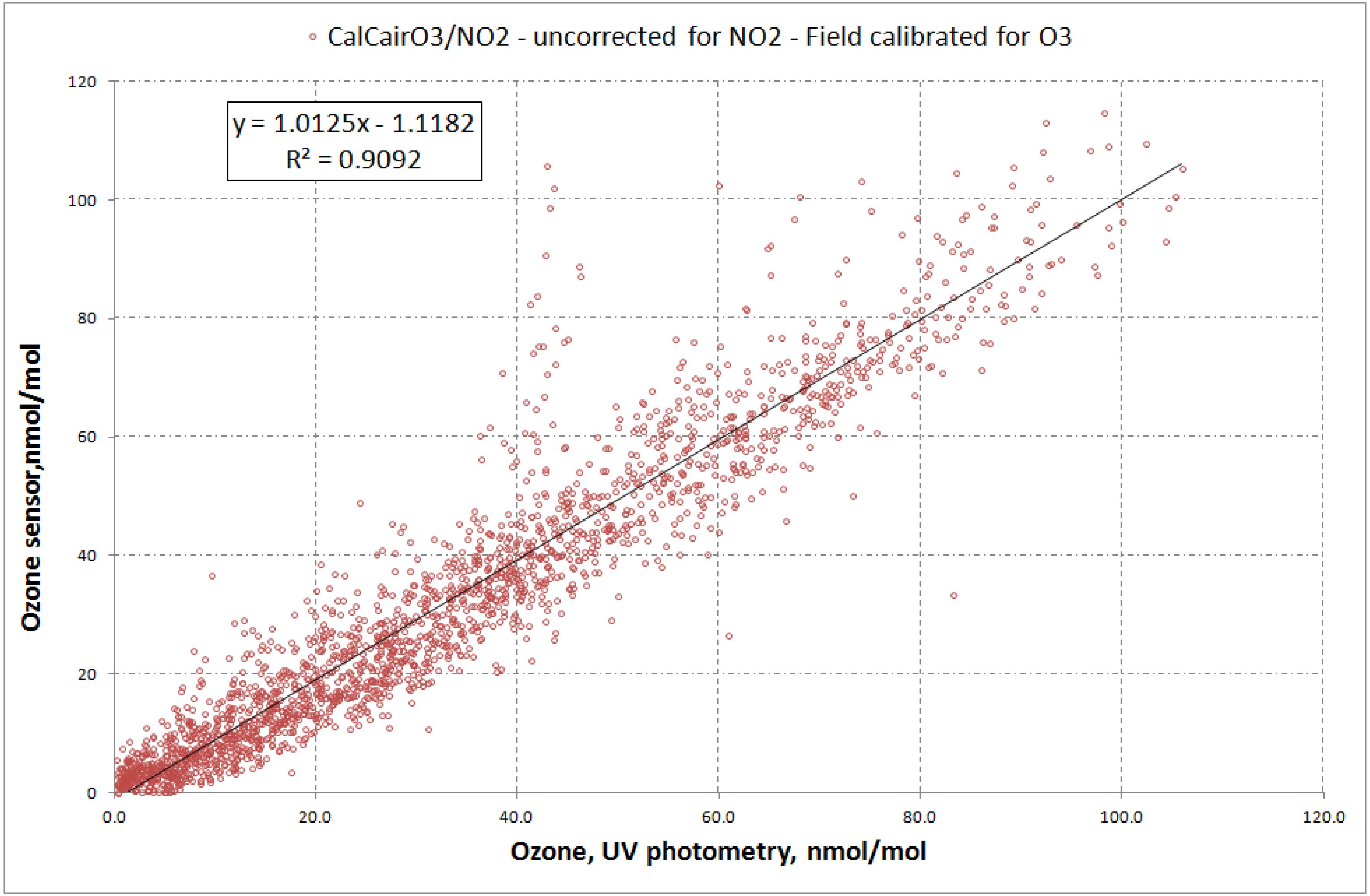

# Uncertainty and DQO

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- $U = 2\,(s^2_{lof} + \cancel{s^2_{bias}} - s_{r,UV}^2\,) < 30\ \%$

| | *U, Hourly values, Validation dataset* |
|---|---|
| 60 ppb | 26 % |
| 90 ppb | 19 % |
| 120 ppb | 17 % |

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# Thank you !

# $O_3$ Sensors

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| Manufacturer | Model | Type |
|---|---|---|
| Unitec s.r.l – IT | $O_3$ Sens 3000 | Resistive |
| Ingenieros Assessores – SP | NanoENvi mote and MicroSAD datalogger, with Oz-47 sensor | |
| αSense - UK | $O_3$ sensors (O3B4) | |
| Citytech – G | Sensoric 4-20 mA Transmitter Board with O3E1 sensor | |
| Citytech – G | Sensoric 4-20 mA Transmitter Board with O3E1F sensor | |
| CairPol – F | CairClip O3 | |
| e2V – CH | MiCS-2610 sensor and OMC2 datalogger, | |
| e2V – CH | MiCS Oz-47 sensor and OMC3 datalogger | |
| IMN2P – FR | Prototype WO3 sensor with MICS-EK1 Sensor Evaluation Kit | |
| FIS - J | SP-61 sensor and evaluation test board | Resistive |

# $NO_2$ Sensors

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| Manufacturer | Model |
|---|---|
| Unitec s.r.l – IT | Sens 3000 |
| Ingenieros Assessores – SP | NanoENvi mote and MicroSAD datalogger, unidentified sensor probably e2v-MICS sensor |
| αSense – UK | $NO_2$ sensors (B4) |
| Citytech – G | Sensoric 4-20 mA Transmitter Board with 3E50/3E100 sensor |
| Citytech – UK | A3OZ EnvirocеL (for now without test board?) |
| MIKES – FI | Prototype graphene sensors |
| InRim – IT | Prototype graphene sensors |
| CairPol – F | CairClip NO2/O3 - filtered |

# Field tests, hourly values

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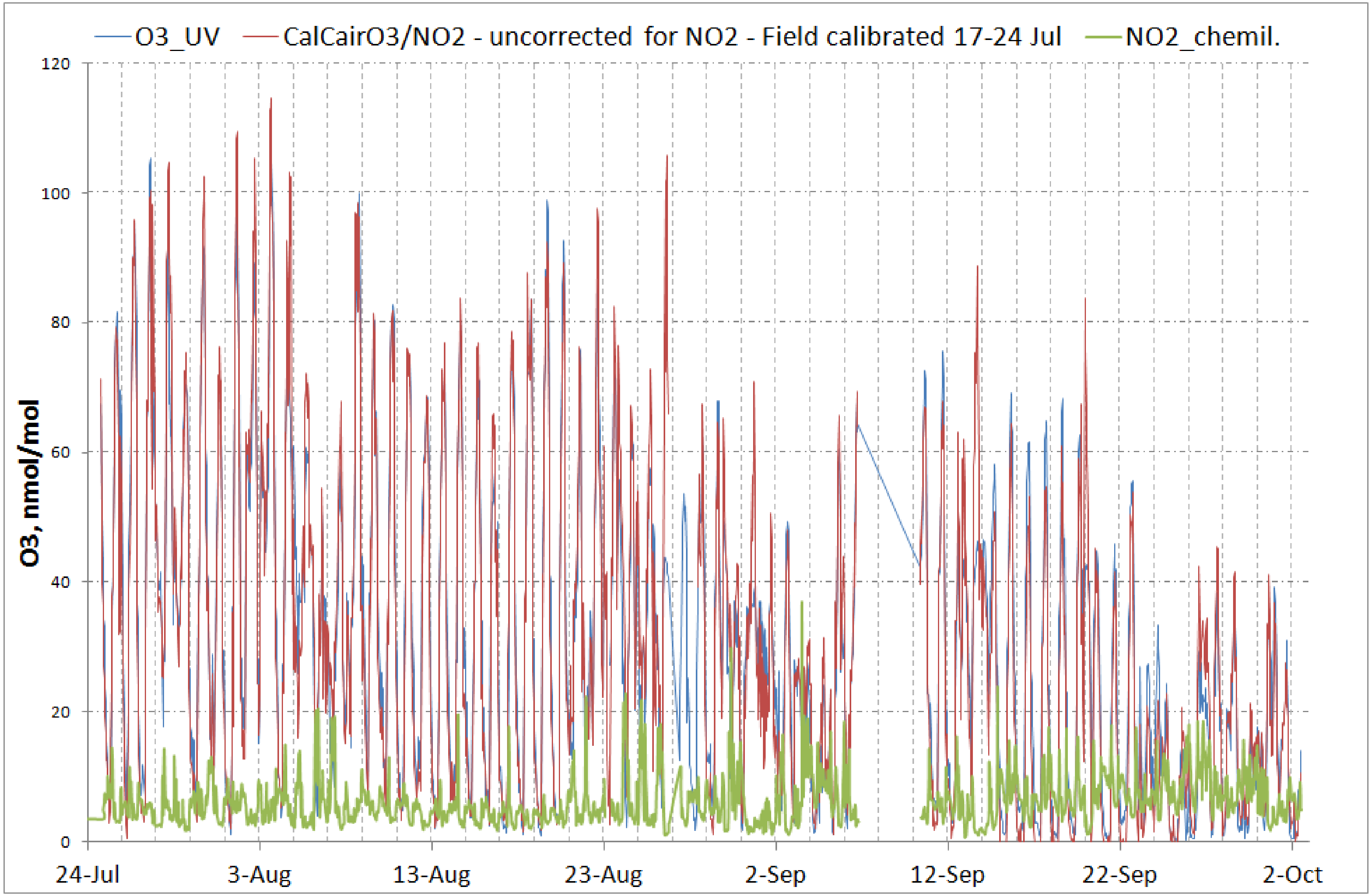

# Hysteresis cycle

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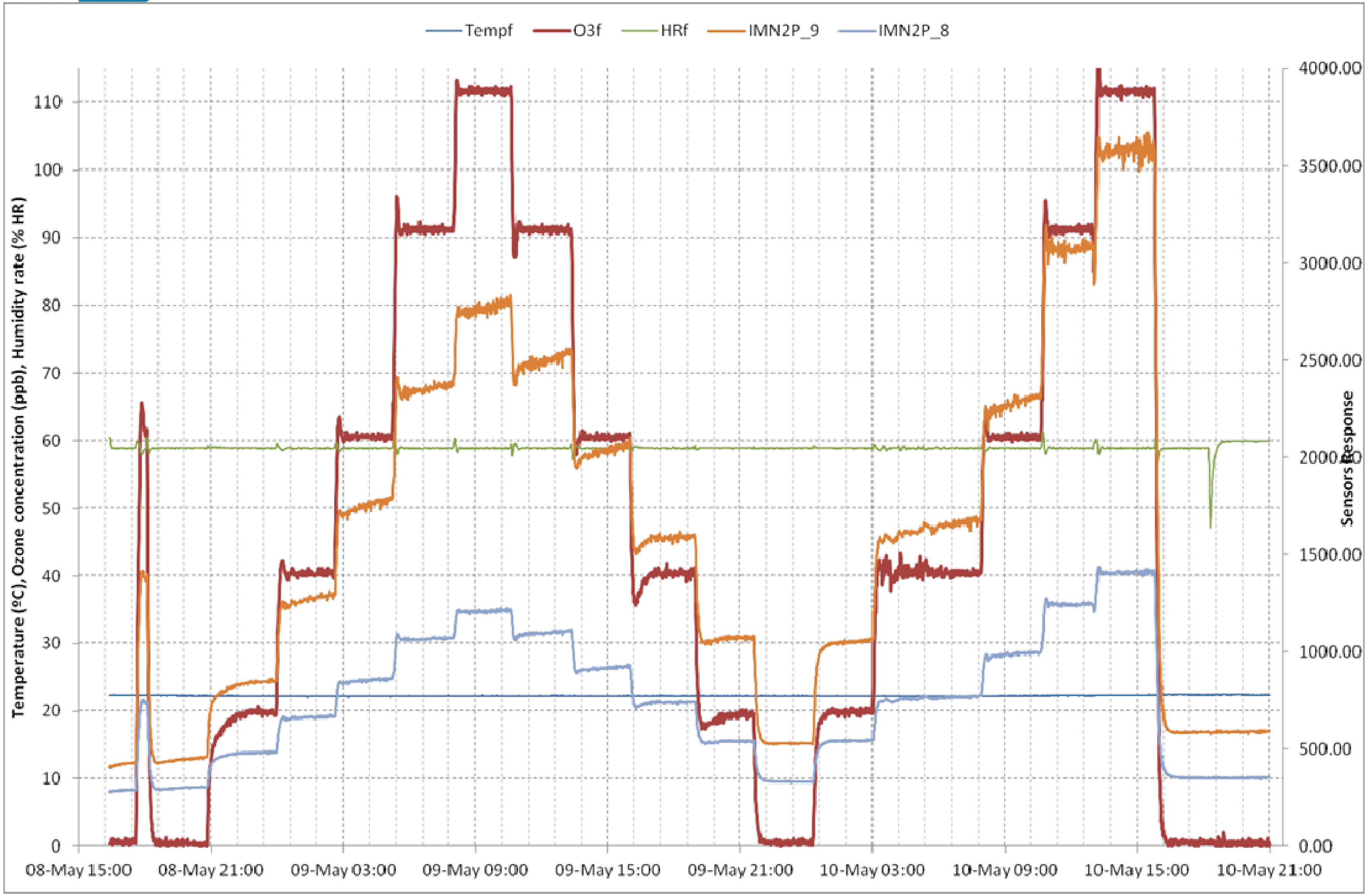

# 4.2 Gaseous Interference

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