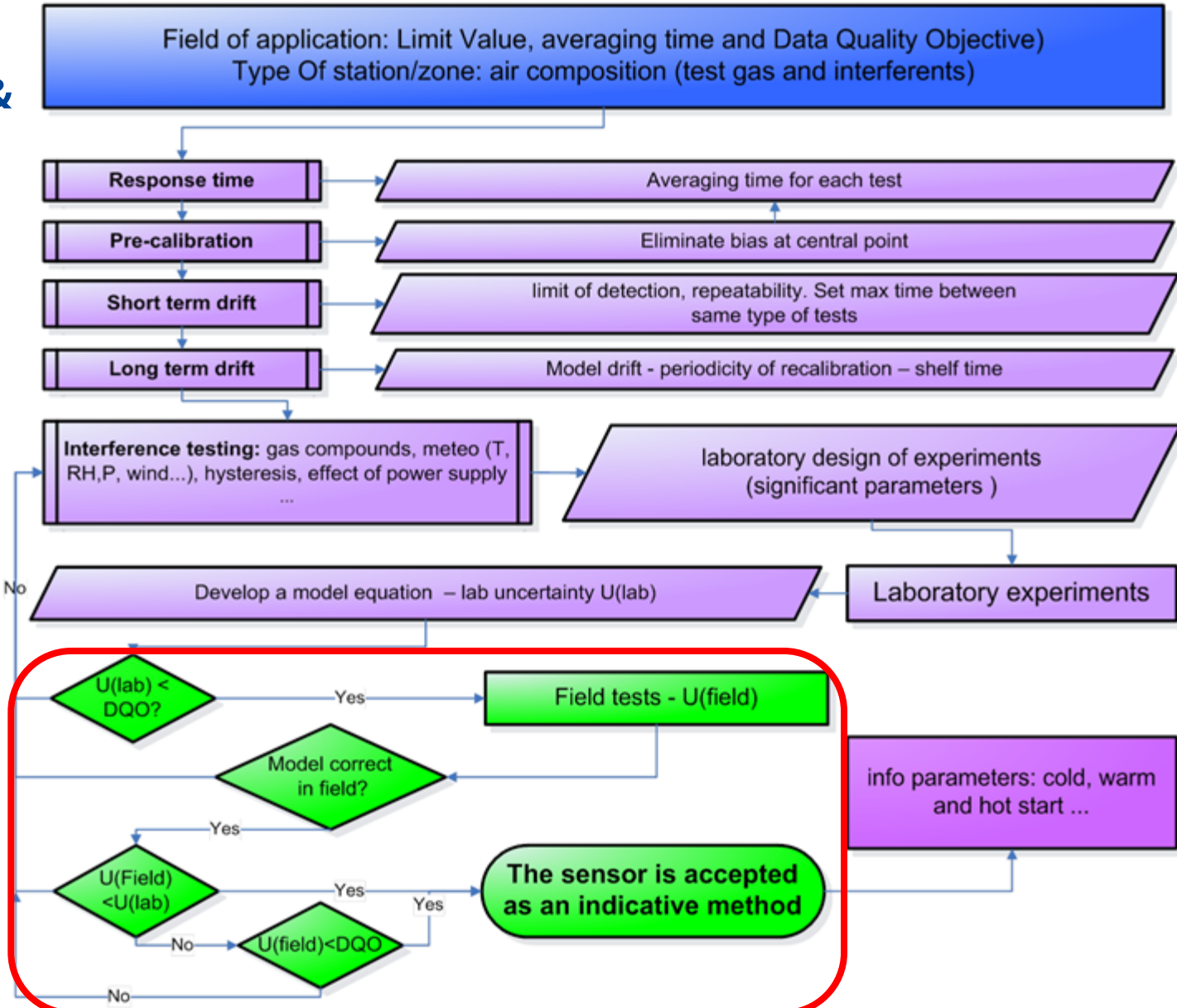




Evaluation & Validation Protocol



Spinelle L, Aleixandre M, Gerboles M. Protocol of evaluation and calibration of low-cost gas sensors for the monitoring of air pollution. EUR 26112. Luxembourg (Luxembourg): Publications Office of the European Union; 2013. JRC83791

Field calibration of a cluster of sensors



Linear regression and multilinear regression

Manufacturer	Model	R ² of linear regression	Multivariate linear model	R ²
αSense	O3 sensors B4	0.07	$O_3 = \frac{Rs - bNO_2 - cNO_2 \cdot H_2O - d}{a}$	0.49
Citytech	O3_3E1F	0.87	$O_3 = \frac{Rs - bNO_2 - c}{a}$	0.91
CairPol	CairclipO3/NO2	Unknown	$O_3 = \frac{Rs - bNO_2 - c}{a}$	Unknown
αSense	NO2-B4	0.06	$NO_2 = \frac{Rs - bO_3 - cT - dRH - e}{a}$	0.56
	NO2 3E 50	0.01	$NO_2 = \frac{Rs - bO_3 - cT - dRH - e}{a}$	0.63
Citytech	NO 3E 100	0.05	Unknown	Unknown
	2710 sensor	0.31	$NO_2 = \frac{Rs - bO_3 - cT - d}{a}$	0.36
e2V	4514 sensor	0.34	$NO_2 = \frac{Rs - bO_3 - cNO - dT - e}{a}$	0.42
CairPol	CairClip NO2	0.37	$NO_2 = \frac{Rs - bO_3 - c}{a}$	0.74
Figaro	5042 sensor	0.17	$CO = \frac{Rs - bT - cRH - d}{a}$	0.23
e2V	4514 sensor	0.56	$CO = \frac{Rs - bT - cRH - d}{a}$	0.58
Edinburgh Sensors	Gascard NG	0.14	$CO_2 = \frac{Rs - bT - cRH - d}{a}$	0.47
ELT Sensors	S-100H	0.58	$CO_2 = \frac{Rs - bT - cRH - d}{a}$	0.62

Linear regression

- ≠ sensors
- depend on the exposure conditions
- include all interfering effects

Multilinear regression

based on laboratory experiments

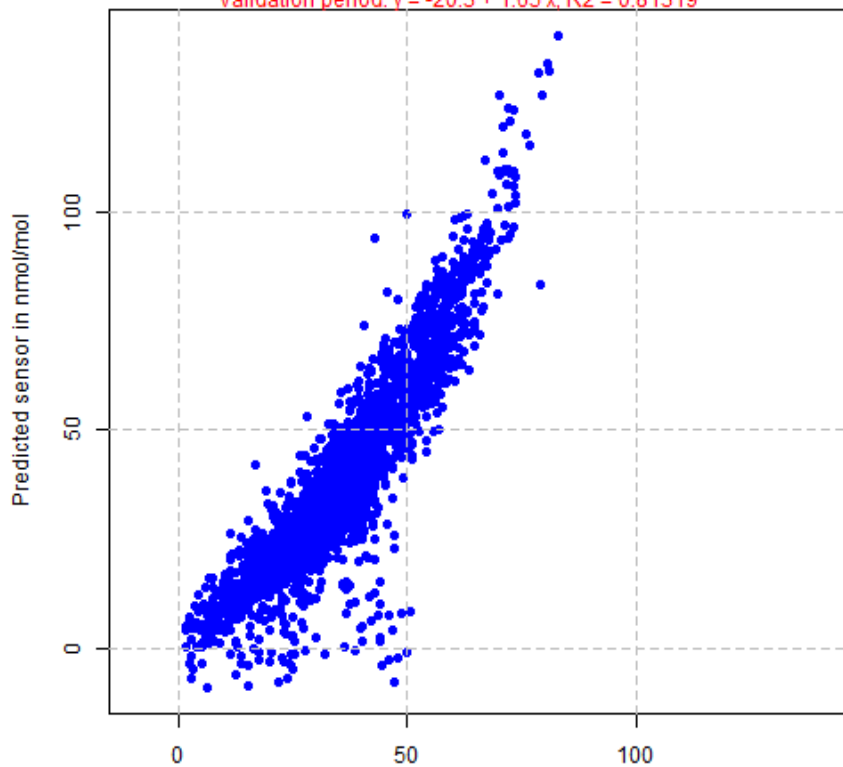
- improve the quality of the data
- needs other variables (gaseous compounds, temperature, humidity...)

Linear regression and multilinear regression

Linear Regression

$$O3_3E1F = f(O3)$$

Validation period: $y = -20.3 + 1.65x$, $R2 = 0.81319$

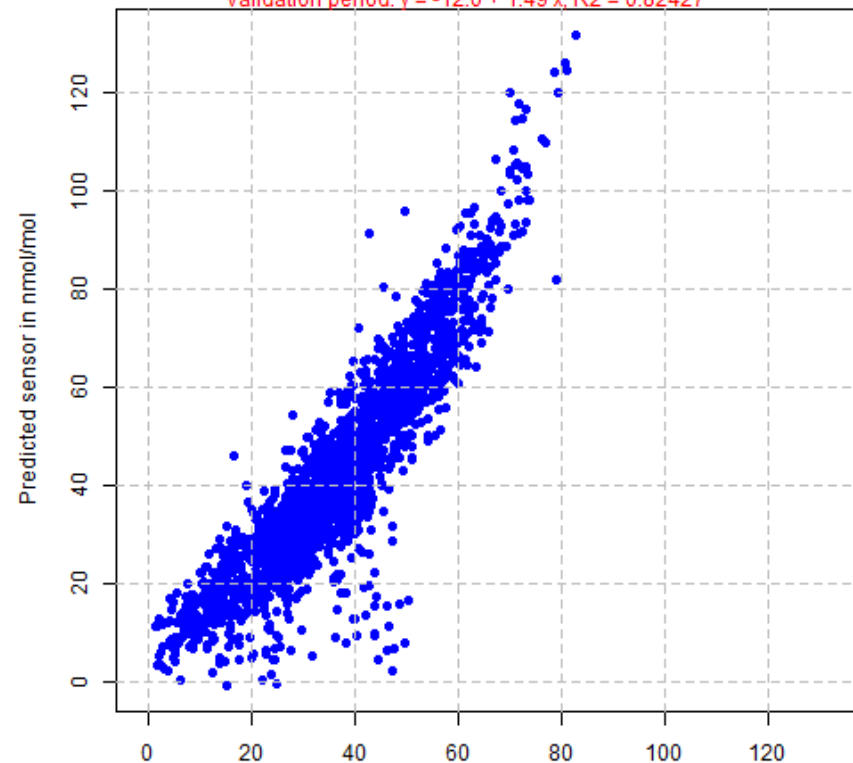


Ozone, UV-photometry nmol/mol

Multi-Linear Regression

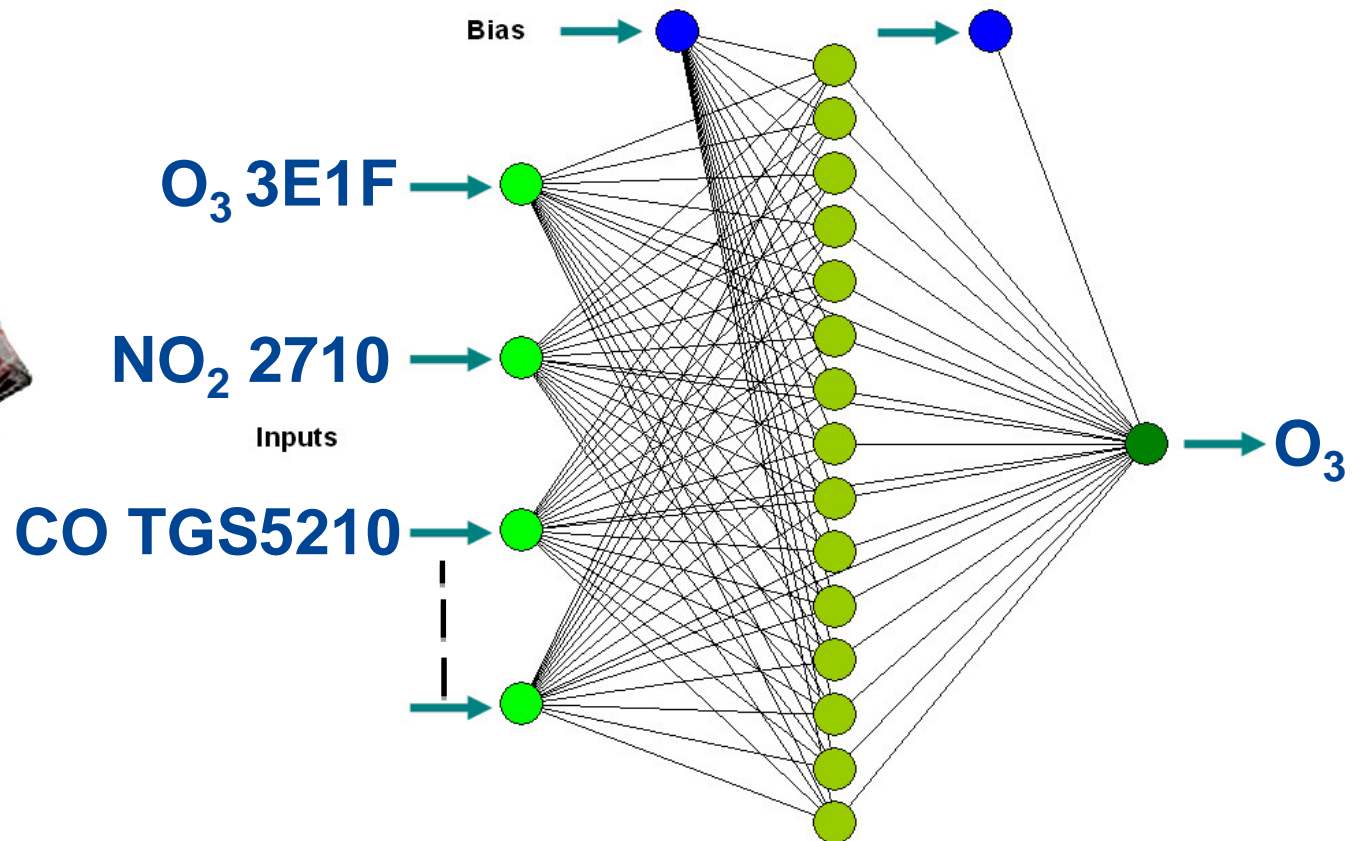
$$O3_3E1F = f(O3, NO2)$$

Validation period: $y = -12.0 + 1.49x$, $R2 = 0.82427$



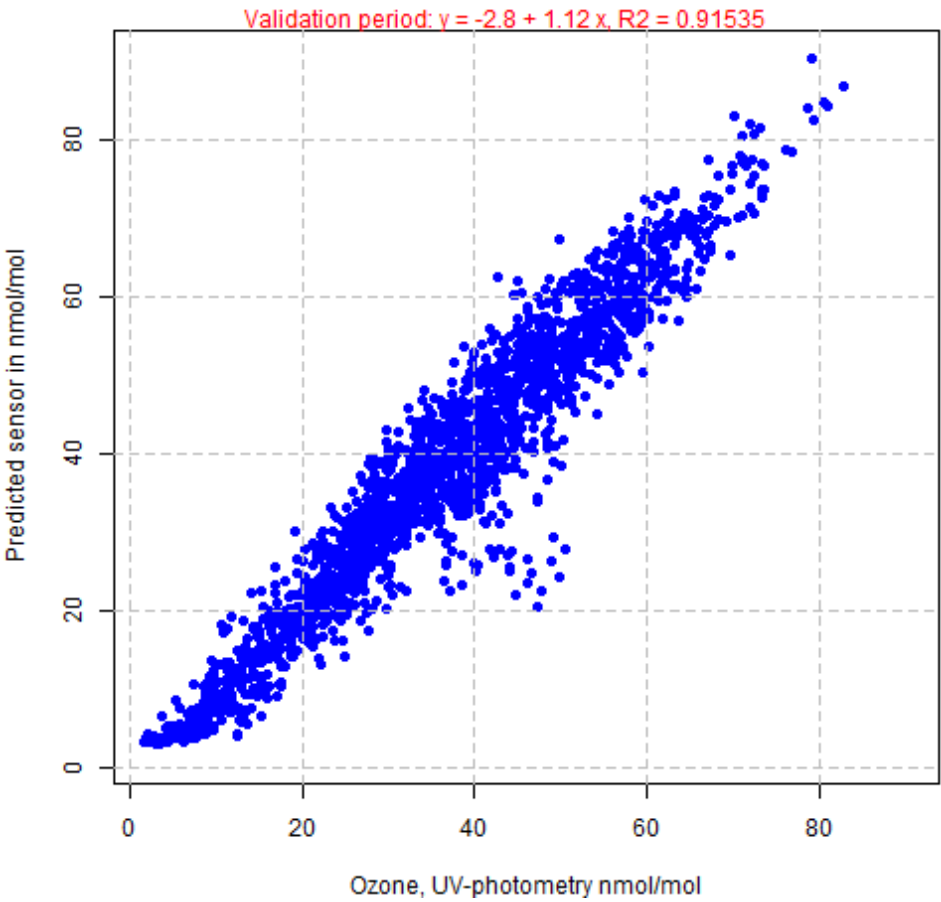
Ozone, UV-photometry nmol/mol

Artificial Neural Network

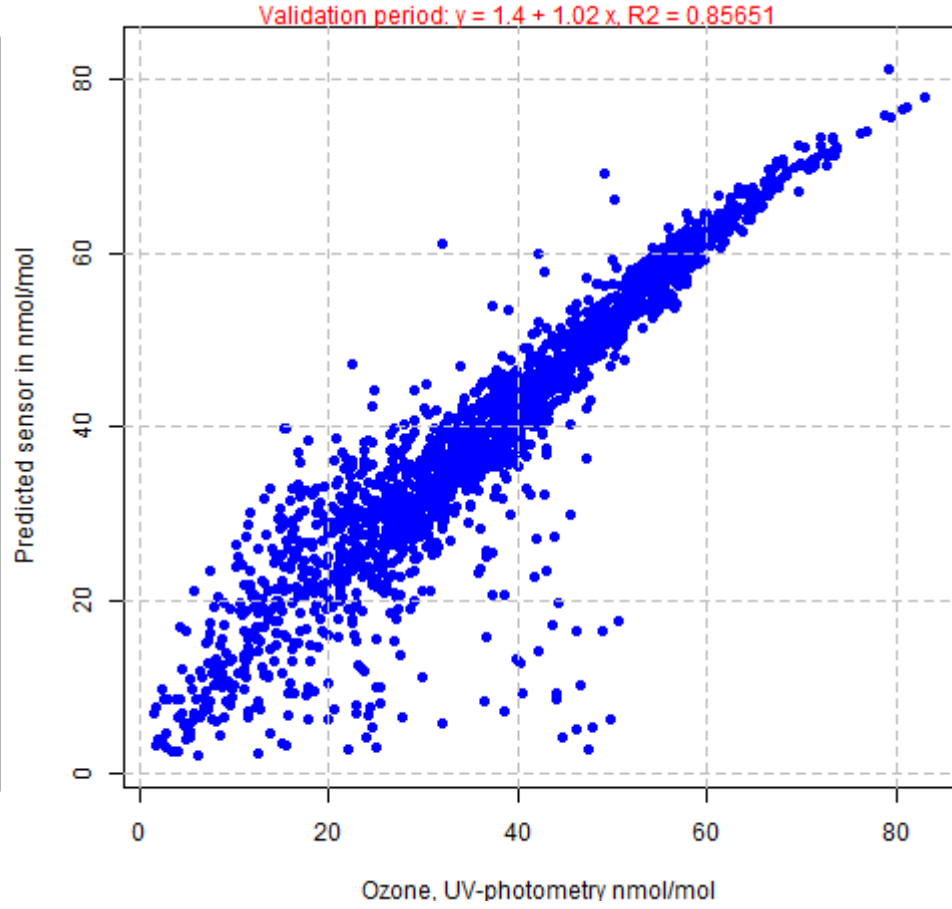


Artificial Neural Network

Art. Neural Network, raw sensor values



Art. Neural Net, calibrated sensor values

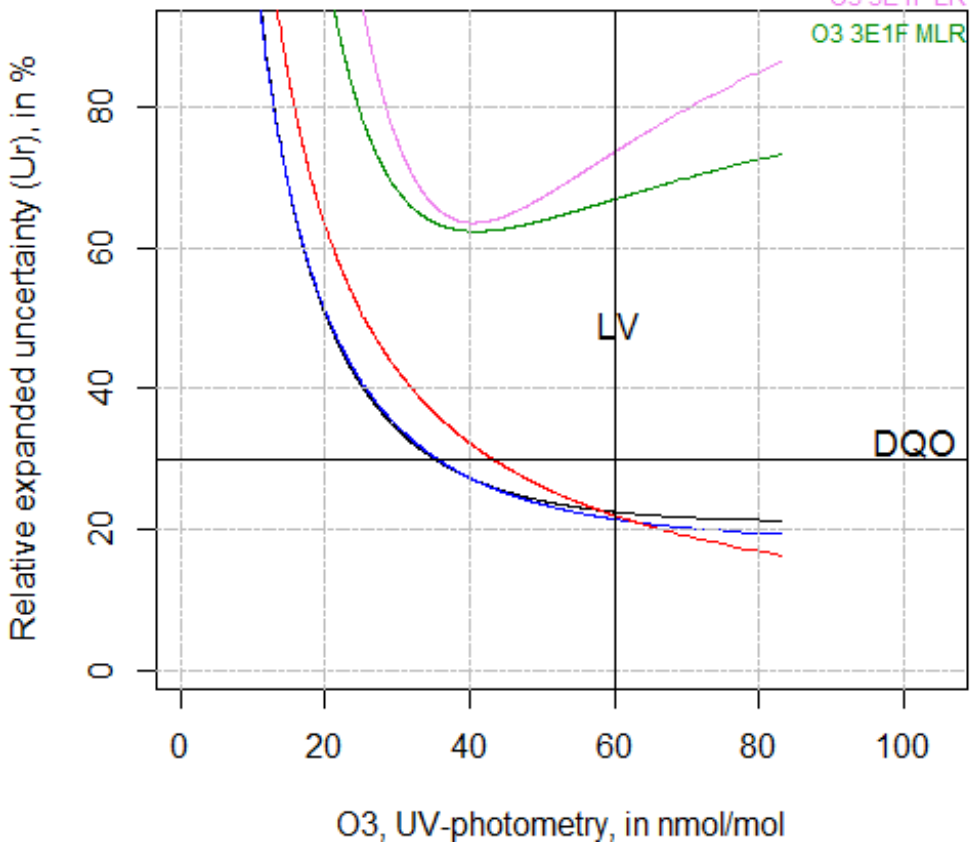


Model Uncertainty


NO₂ NO CO CO₂

ANN raw data
 ANN scaled data
 ANN MLR data
 O3 3E1F LR
 O3 3E1F MLR

Algorithms	Ambient parameters	Inputs
LM	No	Sensor
MLR	No	Sensor + Reference
ANN	No	Sensors
ANN+Std	No	Sensors
ANN+MLR	No	Sensors + Reference



$$U_r(y_i) = 2 \left(\sqrt{\frac{RSS}{(n-2)} - u^2(x_i) + [a + (b-1) \cdot x_i]^2} \right) / y_i$$

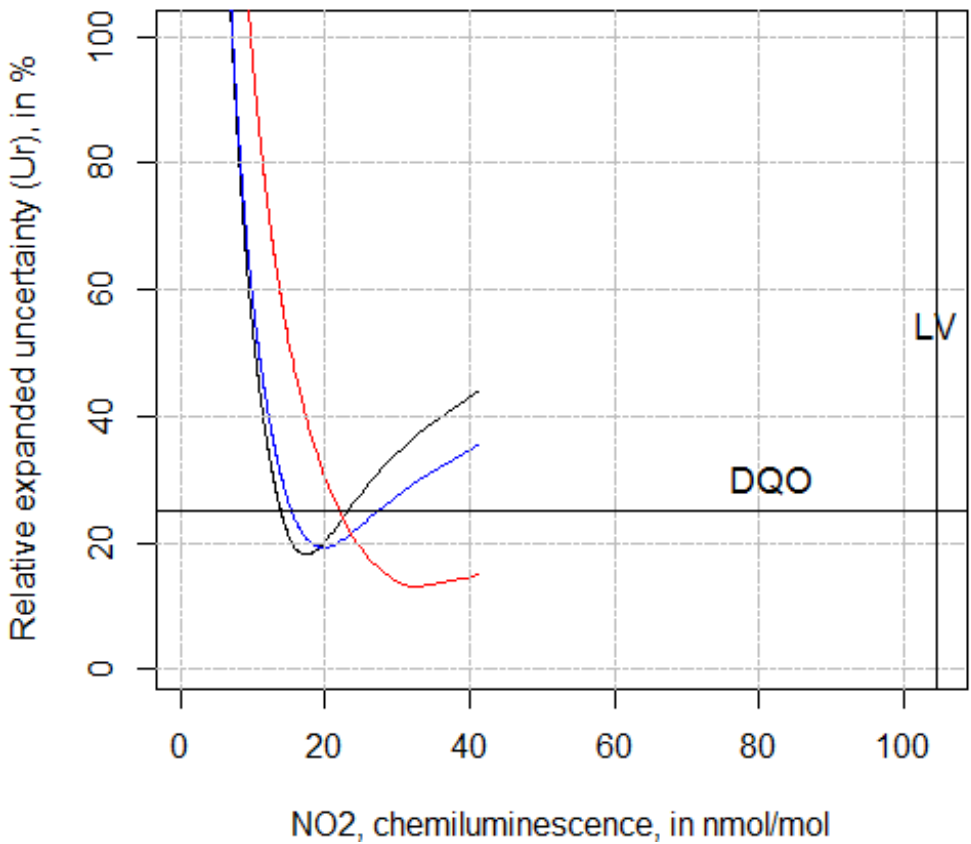
Model Uncertainty

NO CO CO₂

ANN raw data
 ANN scaled data
 ANN MLR data

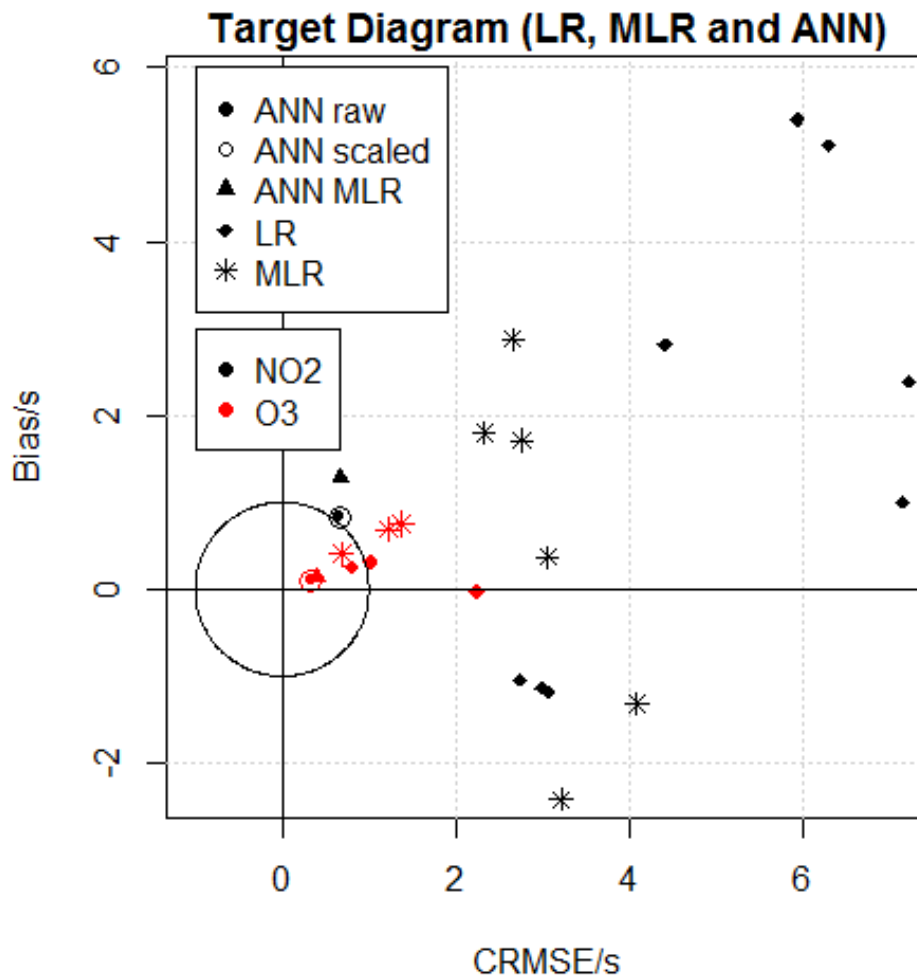
Algorithms	Ambient parameters	Inputs
LM	No	Sensor
MLR	No	Sensor + Reference
ANN	No	Sensors + Abs. Hum.
ANN+Std	No	Sensors + Abs. Hum.
ANN+MLR	No	Sensors + Reference

$$U_r(y_i) = 2 \left(\sqrt{\frac{RSS}{(n-2)} - u^2(x_i) + [a + (b-1) \cdot x_i]^2} \right) / y_i$$



Model Uncertainty - Target Diagram

- **target cycle** = model results are within the observation uncertainty range
- **symbols out** of the target circle = RMSE > s (standard deviation of reference measurements)
- **ANN** show a lower unbiased RMSE (called centered root-mean-square error, CRMSE) and a lower bias

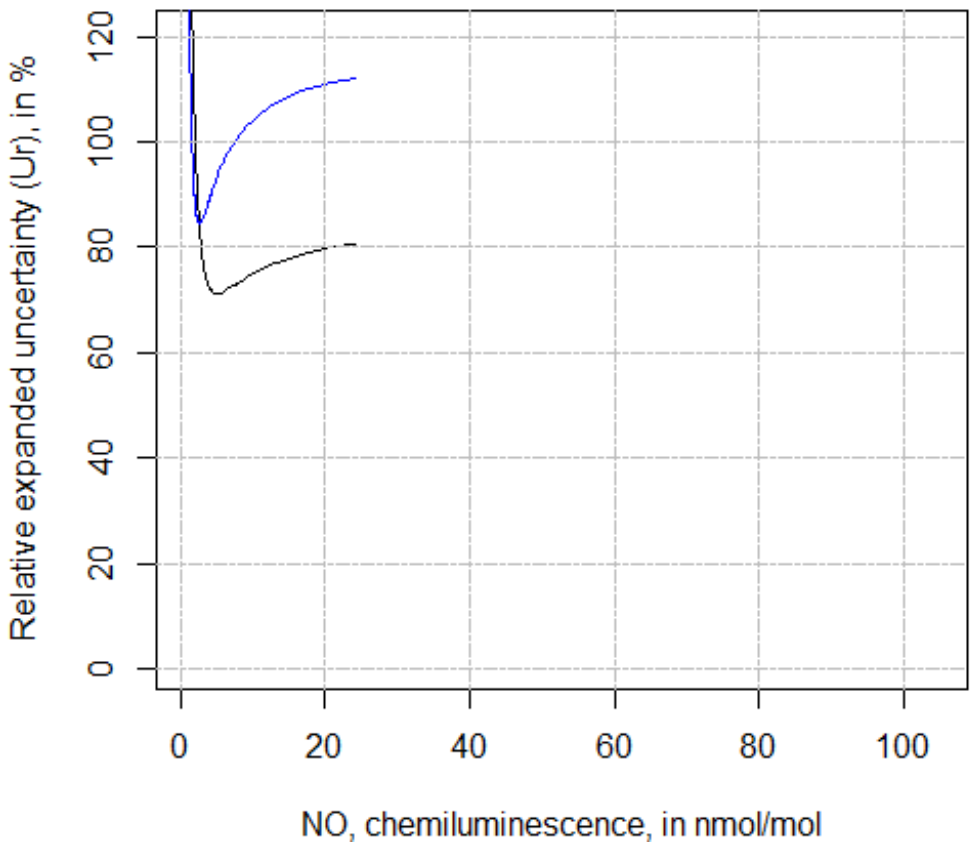


Model Uncertainty

ANN raw data
 ANN scaled data
 ANN MLR data

Algorithms	Ambient parameters	Inputs
LM	No	Sensor
MLR	No	Sensor + Reference
ANN	No	Sensors + T. + Hum.
ANN+Std	No	Sensors + T. + Hum.
ANN+MLR	No	Sensors + Reference

$$U_r(y_i) = 2 \left(\sqrt{\frac{RSS}{(n-2)} - u^2(x_i) + [a + (b-1) \cdot x_i]^2} \right) / y_i$$

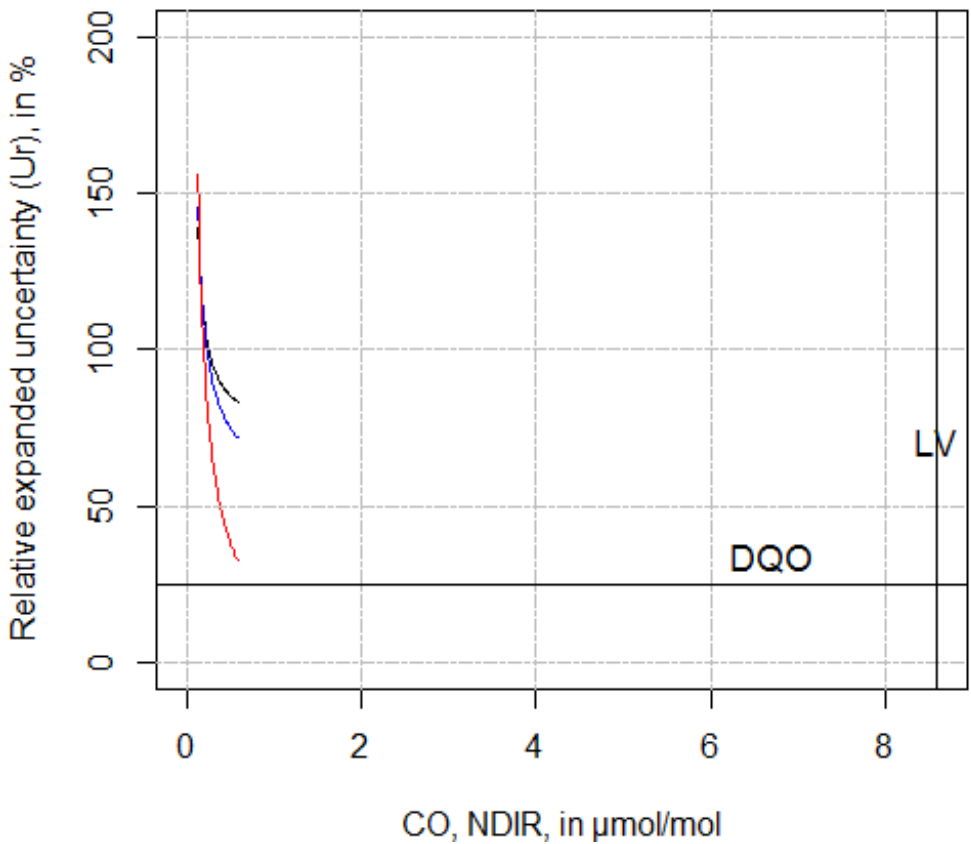


Model Uncertainty



Algorithms	Ambient parameters	Inputs
LM	No	Sensor
MLR	No	Sensor + Reference
ANN	No	Sensors + T. + Hum.
ANN+Std	No	Sensors + T. + Hum.
ANN+MLR	No	Sensors + Reference

$$U_r(y_i) = 2 \left(\sqrt{\frac{RSS}{(n-2)} - u^2(x_i) + [a + (b-1) \cdot x_i]^2} \right) / y_i$$



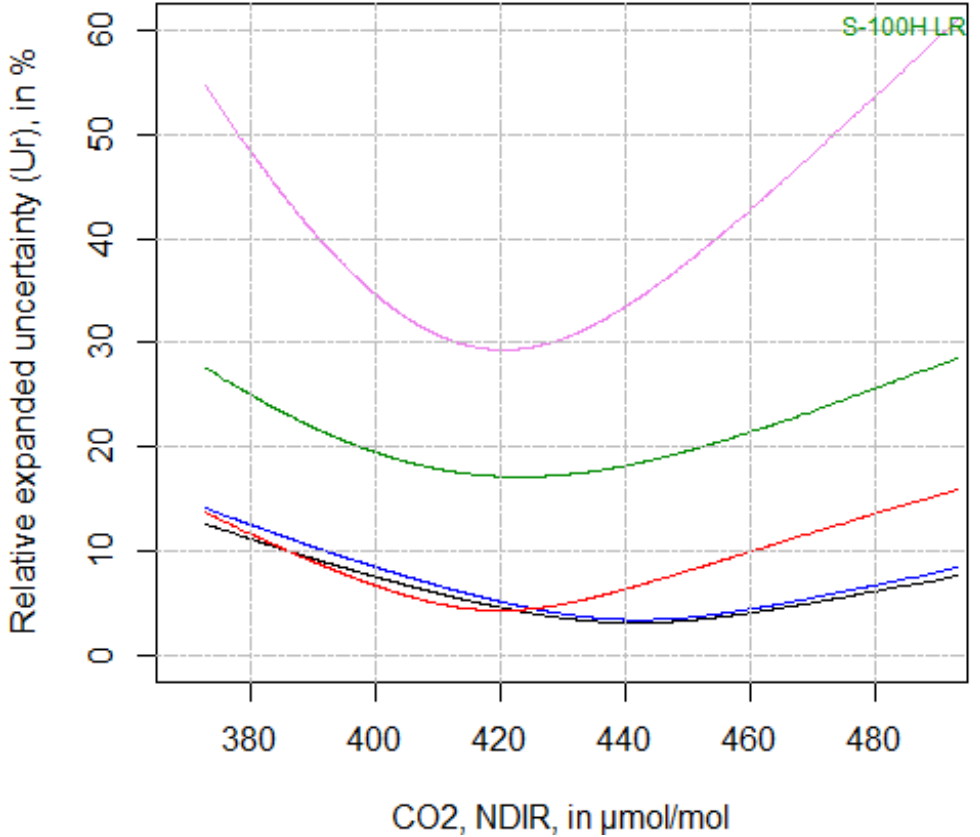
Model Uncertainty



ANN raw data
ANN scaled data
ANN MLR data
S-100H MLR
S-100H LR

Algorithms	Ambient parameters	Inputs
LM	No	Sensor
MLR	No	Sensor + Reference
ANN	No	Sensors
ANN+Std	No	Sensors
ANN+MLR	No	Sensors + Reference

$$U_r(y_i) = 2 \left(\sqrt{\frac{RSS}{(n-2)} - u^2(x_i) + [a + (b-1) \cdot x_i]^2} \right) / y_i$$



Conclusion calibration methods for the whole cluster of sensors

- The DQO for indicative methods can be met for O₃, likely for NO₂. High uncertainty for NO and CO (>75%). For CO₂, low uncertainty down to about 5%.
- Linear and Multilinear regression gives the highest U.
- ANN methods: higher R² and lower CRMSE -> lower U; lower bias to reference data (slopes and intercept nearer to 1 and 0, respectively).
- Reference data (meteo / gas) does decrease measurement uncertainty for the ANN methods.
- ANN can solve cross sensitivity issues from which suffers the major part of sensors (gaseous interference, temperature/humidity dependence).

Thank You...

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