VAQUUMS

Performance evaluation of five low-cost nitrogen dioxide sensors in the field

Author: Christina Matheeussen

1 Index

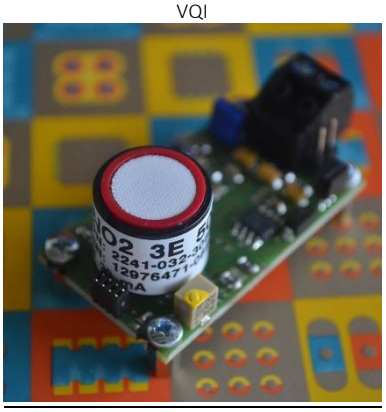
2 Introduction

2.1 General information

This report describes the field comparison of 5 types (Table 1) of low-cost NO_2 sensors. Full details of the testing are provided in the test protocol (https://vaquums.eu/sensor-db/tests/protocols/life-vaquums_testprotocol_final.pdf).

Sensor units were co-located at the R801 urban background measurement site of VMM in Borgerhout, Antwerp (Belgium) for about 400 days (from February 23, 2019 until March 30 2020). The NO_2-sensors were compared to the **reference method**, i.e. the chemiluminescence analyser 42i of ThermoFisher Scientific measuring at a high time resolution (10 s) and operating according to standard EN14211. Sensors usually reported data per second (Envea Cairclip per 15 minutes) but these were aggregated as minute, 5 minute, hourly and daily averages. The hourly level was chosen as the main aggregation level for most analyses.

Table 1: NO_2-sensors that were tested in the VAQUUMS field campaign together with the abbreviation used in this report.

Alphasense B43F NO_2 VQH 	Citytech 3E50 NO_2 VQI 	Membrapor C1 NO_2 VQK 
Membrapor C20 NO_2 VQL 	Envea Cairclip NO_2 VQS 	

For each sensor type we discuss the following points:

2.1.1 Validation and data coverage

Specific issues with the validation of the sensors are mentioned here, in addition the number of available and not available minute and hourly data per validation code (0: valid, -1: suspicious, -2: invalid, 1: missing) are shown.

2.1.2 Uncalibrated data and sensor data calibrated with parameters from linear regression

2.1.2.1 Calibration parameters

A calibration function was established by assuming linearity between the sensor data and the reference data. Orthogonal regression on the hourly data was used to establish the calibration function. The data from February 23, 2019 - March 31, 2019 were used to establish the calibration function.

The evaluation of the sensors was done on the the data in the remaining period from April 1, 2019 -March 30, 2020.

For some sensor types we found almost no correlation ($R^2 < 0.1$) between the uncalibrated sensor data and the reference NO_2 data. In this case, the parameters of the linear regression are not well defined. Therefore, the parameters were not calculated nor used for these sensor types.

2.1.2.2 Comparison of uncalibrated and calibrated sensor data with the reference data

The comparison is presented as time plots and scatter plots. The ratio of the sensor data versus the reference data was calculated and presented as density plots.

2.1.2.3 Influence of time, temperature, relative humidity and O_3 on uncalibrated sensor data

The ratio sensor data versus reference data is plotted in function of time, temperature, relative humidity and O_3. Temperature, relative humidity and O_3 are parameters with a known effect on (some) NO_2 sensors. The scatter plot in function of time is used to evaluate possible drift of the sensor.

2.1.2.4 Descriptive parameters

R^2, mean bias and the between sampler uncertainty (u_{bs}) are presented.

2.1.2.5 Relative expanded uncertainty

Annex 1 of Directive 2008/50/EG gives data quality objectives for ambient air quality assessment. The maximum relative expanded uncertainty at the limit value (LV) for indicative measurements is 25 %, for objective estimation 75 %. The LV for hourly NO_2 concentrations is 200 µg/m^3, not to be exceeded more than 18 times a year. The LV for a yearly average is 40 µg/m^3. We use the LV for the yearly average for evaluating the relative expanded uncertainty of the daily (calibrated) sensor data.

Additionally we evaluate the relative expanded uncertainty of the (calibrated) sensor data at the upper and lower assessment thresholds (UAT and LAT).

The table below summarizes the LV and the assessment thresholds for NO_2.

Table 2: Limit value (LV), upper assessment threshold (UAT) and lower assessment threshold (LAT) for hourly and yearly NO_2 values.

Averaging time	LV	UAT	LAT
1 hour	200 µg/m^3	140 µg/m^3	100 µg/m^3
1 year	40 µg/m^3	32 µg/m^3	26 µg/m^3

The relative expanded uncertainties of the (calibrated) sensor data are also calculated and plotted at NO_2 hourly concentrations of 10 to 200 µg/m^3 and at NO_2 daily concentrations of 10 to 100 µg/m^3.

The relative expanded uncertainty is calculated according to the 'Guide to the demonstration of equivalence of ambient air monitoring methods'. In case of low correlation ($R^2 < 0.1$) between the sensor data and the reference data, the relative expanded uncertainty is not calculated. The parameters of the regression line are presented in a table.

2.1.2.6 Conclusions

The conclusions are based on tables and plots mentioned above.

2.1.3 Sensor data calibrated with parameters from multiple linear regression (MLR)

2.1.3.1 Calibration parameters

Besides linear regression, multiple linear regression (MLR) is a widely used technique to calibrate sensor data against reference data[1]. MLR includes the use of more than one independent variable to improve the quality of the calibration.

Two MLR calibration functions were calculated:

- a MLR function using reference NO_2, relative humidity and temperature as independent variables. This approach has the advantage that no reference data are needed for the calibration of the sensor data during the evaluation period,
- a MLR calibration function using reference NO_2, relative humidity, temperature and O_3 as independent variables.

MLR makes several assumptions regarding the variables. One of the assumptions is a linear relation between the dependent variable (the uncalibrated sensor data) and the

[1]Karagulian, F., Gerboles, M., Barbiere, M., Kotsev, A., Lagler, F., Borowiak, A., *Review of sensors for air quality monitoring*, EUR 29826 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-09255-1, doi:10.2760/568261, JRC116534

independent variables (reference NO_2, relative humidity, temperature and O_3). In annex 1 correlation charts can be found for all sensors where this assumption can be checked. Another assumption of MLR is the independence of the independent variables. As expected correlation is noticed between the independent variables reference NO_2, relative humidity, temperature and O_3. The correlation coefficients are also shown in annex XX.

Several approaches can be followed to select the most significant variables to include in the MLR function but the further elaboration of the MLR functions is considered to be outside the objective of the project.

The same periods for calibration/evaluation are used for the multiple linear regression as for the linear regression.

2.1.3.2 Comparison of the calibrated sensor data with the reference data

As for the sensor data calibrated with the parameters of the linear regression, the comparison is presented as time plots, scatter plots and density plots of the ratios calibrated sensor data versus reference data. In case of almost no correlation ($R^2 < 0.1$) between the calibrated sensor data and the reference data; the plots are not shown.

2.1.3.3 Influence of time, temperature, relative humidity and O_3

As for the sensor data calibrated with the parameters of the linear regression, the ratio sensor/reference is plotted in function of time, temperature, relative humidity and O_3. In case of low correlation ($R^2 < 0.1$) between the calibrated sensor data and the reference data, the plots are not shown.

2.1.3.4 Descriptive parameters

R^2, mean bias and the between sampler uncertainty (u_{bs}) are presented for the calibrated sensor data.

2.1.3.5 Relative expanded uncertainty

The calculation and the evaluation is done as described in the previous section.

2.1.3.6 Conclusions

The conclusions are based on tables and plots mentioned above.

2.2 Validation and calibration

2.2.1 Validation

The two main processes involved in the sensor evaluation are validation and calibration. Data validation was done on 15-minutes values for the Envea Cairclip sensors and on minute values for the other sensors. Both invalid and suspicious data were left out and only valid data are used for the evaluation of several characteristics (information on validation, see technical manual). The evaluation of the sensor characteristics is mainly done on hourly data.

2.2.2 Calibration

The evaluation of the performance is done on:

- the uncalibrated sensor data **NO2_s_2**
- the sensor data **NO2_s_lab2:** sensor data after calibration with the linear regression parameters from the laboratory study. This evaluation is included in the annexes.

The calibration function is of the type:

*NO2_s_2 = a *NO2_ref + intercept*

The values for *a* and *intercep*t can be found in the tables with the calibration parameters.

The resulting function applied to the sensor data from February 23 2019 - March 30 2020 is of the type:

NO2_s_lab2 = (NO2_s_2 – intercept) / a

- the sensor data **NO2_s_1mLR2** after calibration with the linear regression parameters. The field campaign data from February 23, 2019 - March 31, 2019 were used to establish the calibration function.

The calibration function is of the type:

*NO2_s_2 = a *NO2_ref + intercept*

The values for *a* and *intercep*t can be found in the tables with the calibration parameters.

The resulting measurement function applied to the sensor data during the evaluation period is of the type:

NO2_s_1mLR2 = (NO2_s_2 – intercept) / a

- the sensor data **NO2_s_1mMLR2** after calibration with the parameters of the multiple linear regression (MLR) using reference NO_2, relative humidity (RH) and temperature (T) as variables. The field campaign data from February 23, 2019 - March 31, 2019 were used to establish the calibration function.

The calibration function is of the type:

*NO2_s_2 = a *NO2_ref + c*T + d*RH + intercept*

The values for *a, c ,d* and *intercep*t can be found in the tables with the calibration parameters.

The resulting function applied to the sensor data during the evaluation period is of the type:

*NO2_s_1mMLR2 = (NO2_s_2 - c*T - d*RH - intercept) / a*

- the sensor data **NO2_s_1mMLRext2** after calibration with the parameters of the multiple linear regression (MLR) using reference NO_2, relative humidity, temperature and O_3 as variables. The field campaign data from February 23, 2019 - March 31, 2019 were used to establish the calibration function.

The calibration function is of the type:

*NO2_s_2 = a *NO2_ref + b*O_3 + c*T + d*RH + intercept*

The values for *a, b, c ,d* and *intercep*t can be found in the tables with the calibration parameters.

The resulting function applied to the sensor data during the measurement period is of the type:

NO2_s_1mMLRext2 = (NO2_s_2 - bO_3 - c*T - d*RH – intercept) / a*

2.3 Conditions during field campaign

Figure 1 and 2 show the time plots of the hourly and daily NO_2 values measured with the reference instrument. Figure 3 and 4 show the histograms of the hourly and daily NO_2 values. Most NO_2 hourly values are below 100 µg/m^3. No hourly values higher than 200 µg/m^3 occur. Most NO_2 daily values are below 60 µg/m^3. No daily values higher than 100 µg/m^3 occur.

The data from February 23, 2019 - March 31, 2019 were used to establish the calibration function. The evalution of the sensors was done on the the data in the remaining period from April 1, 2019 -March 30, 2020. The average NO_2-concentration during the field campaign was 29.3 µg/m^3. During the calibration period the average NO_2-concentration was somewhat higher (35.5 µg/m^3) than during the evaluation period (28.6 µg/m^3).

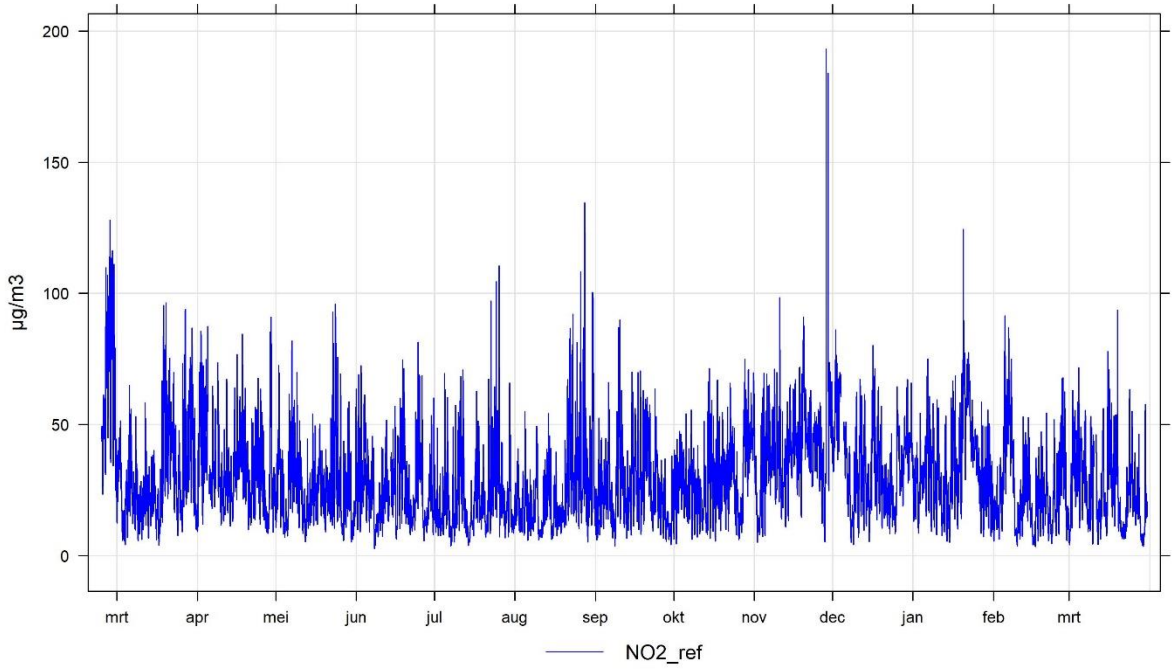


Figure 1: Time plot of hourly NO_2 values (µg/m^3) measured with the reference instrument during the field campaign.

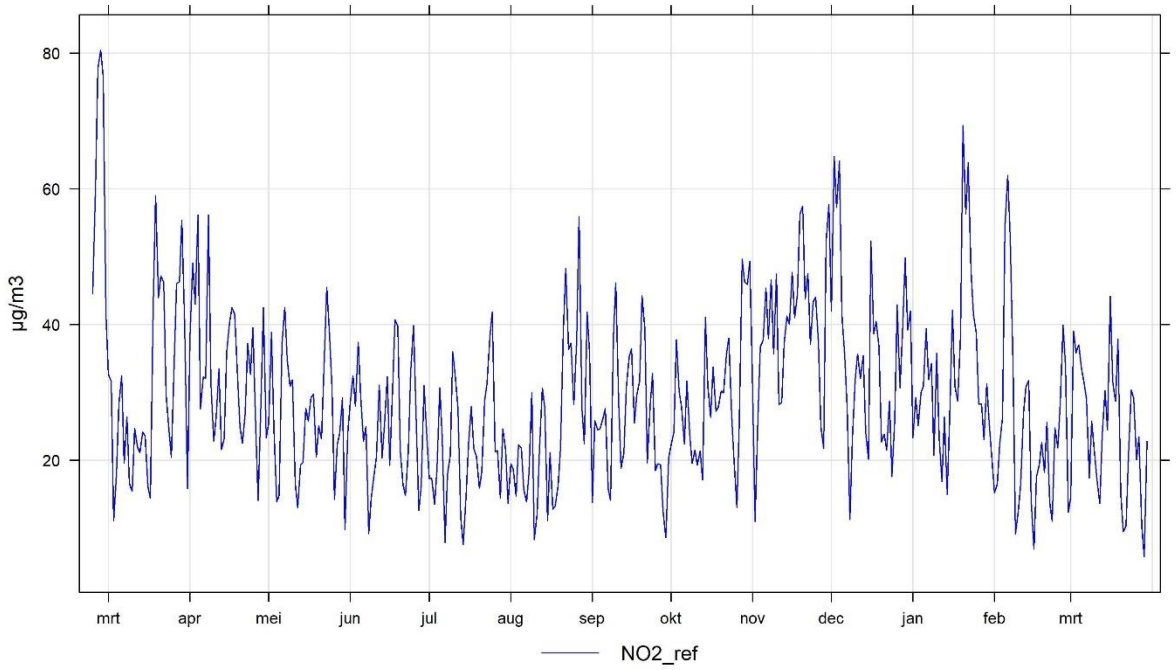


Figure 2: Time plot of daily NO_2 values (µg/m³) measured with the reference instrument during the field campaign.

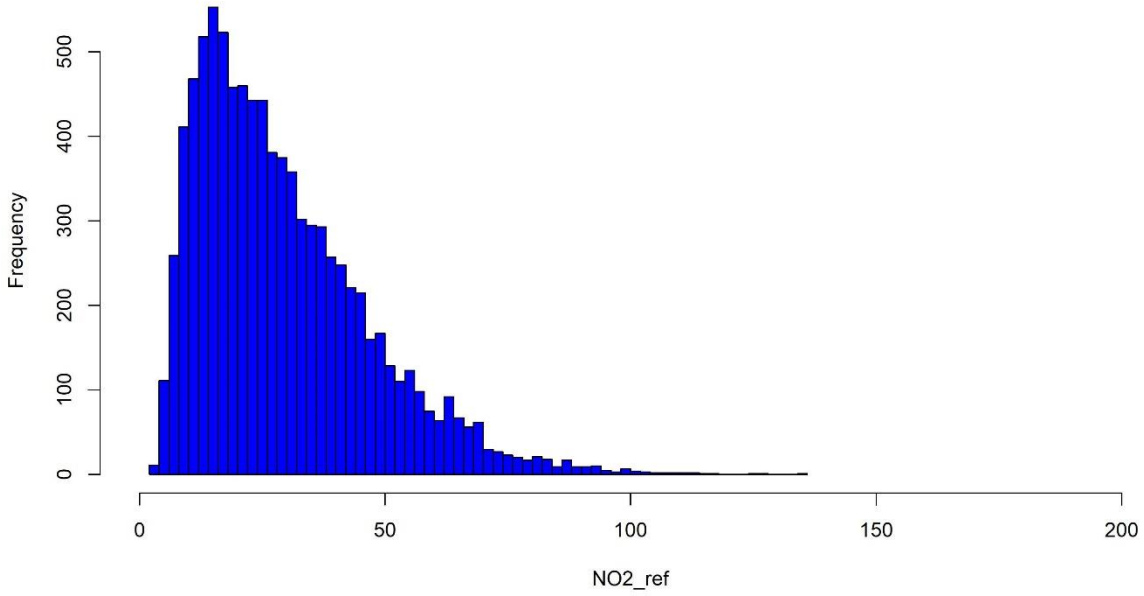


Figure 3: Histogram of hourly NO_2 concentrations (µg/m³) measured with the reference instrument during the field campaign

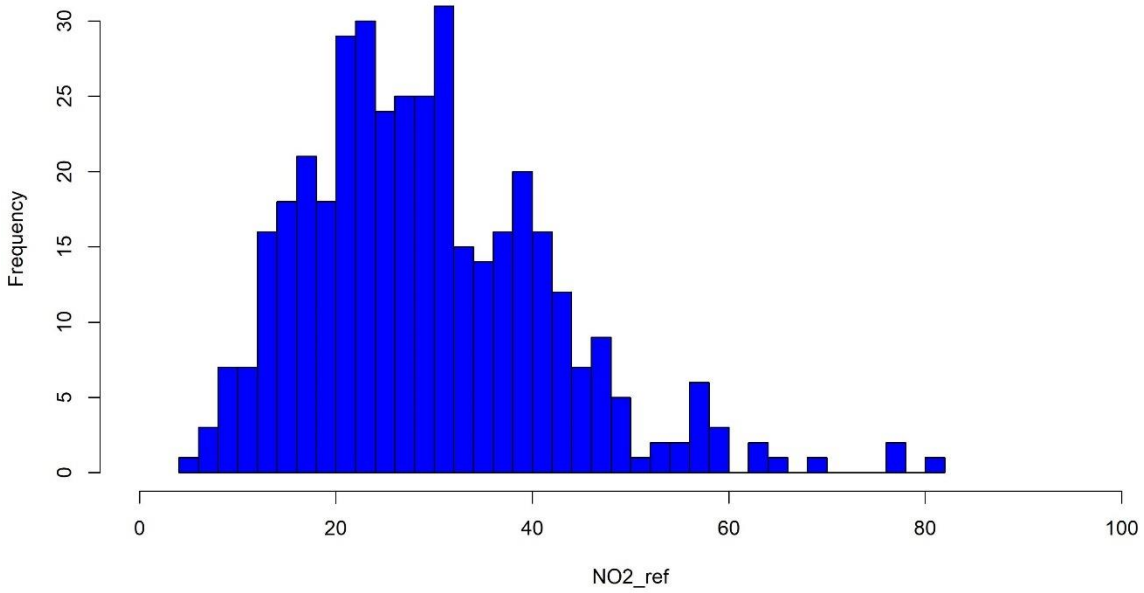


Figure 4: Histogram of daily NO_2 concentrations ($\mu g/m^3$) measured with the reference instrument during the field campaign

Figure 5 shows the variation in hourly values of temperature and relative humidity during the field campaign. Figure 6 and 7 show the histogram of the hourly relative humidity and temperature.

The average temperature and relative humidity in Borgerhout during the whole field campaign were 12.5 °C and 74% respectively. The average temperature and relative humidity were rather similar during the calibration period and validation period. During the calibration period the average temperature was 9.8 °C and the relative humidity was 72 %. During the evaluation period the average temperature was 12.8 °C and the relative humidity was 74 %. The winter 2019-2020 was warm: the minimum temperature was -1.2 °C in Borgerhout. During the calibration period the minimum temperature was 3.0°C. As a consequence the sensors are not tested at extreme negative temperatures during this field campaign.

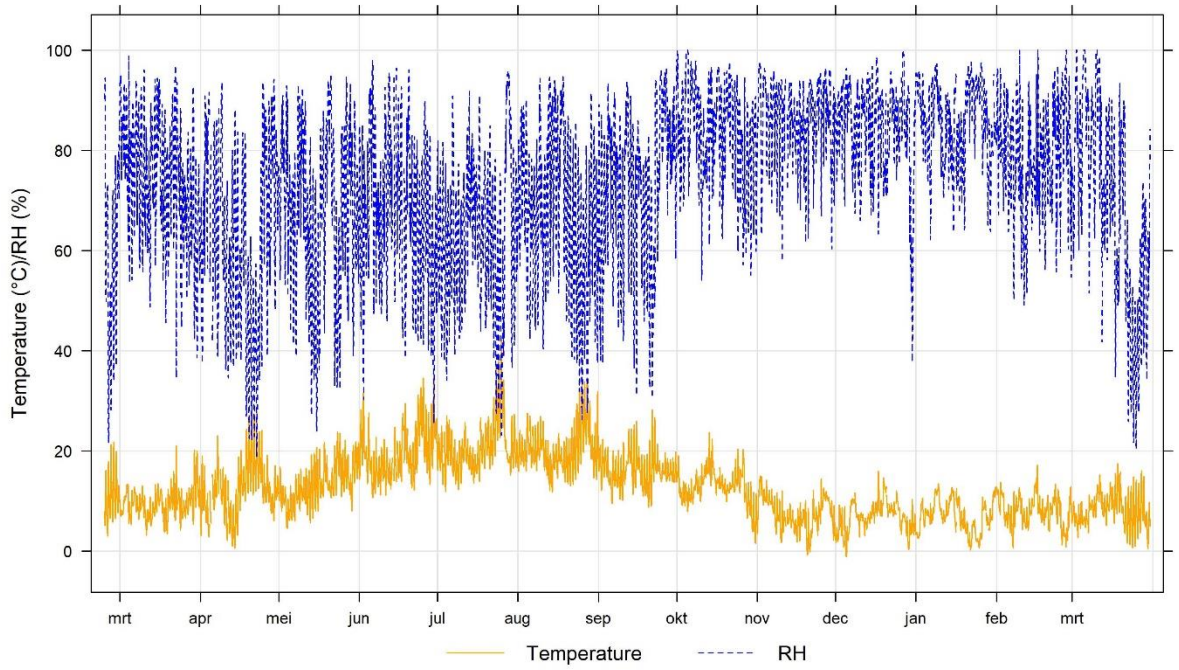


Figure 5: Time plot of hourly temperature (°C) and relative humidity (%) during the field campaign

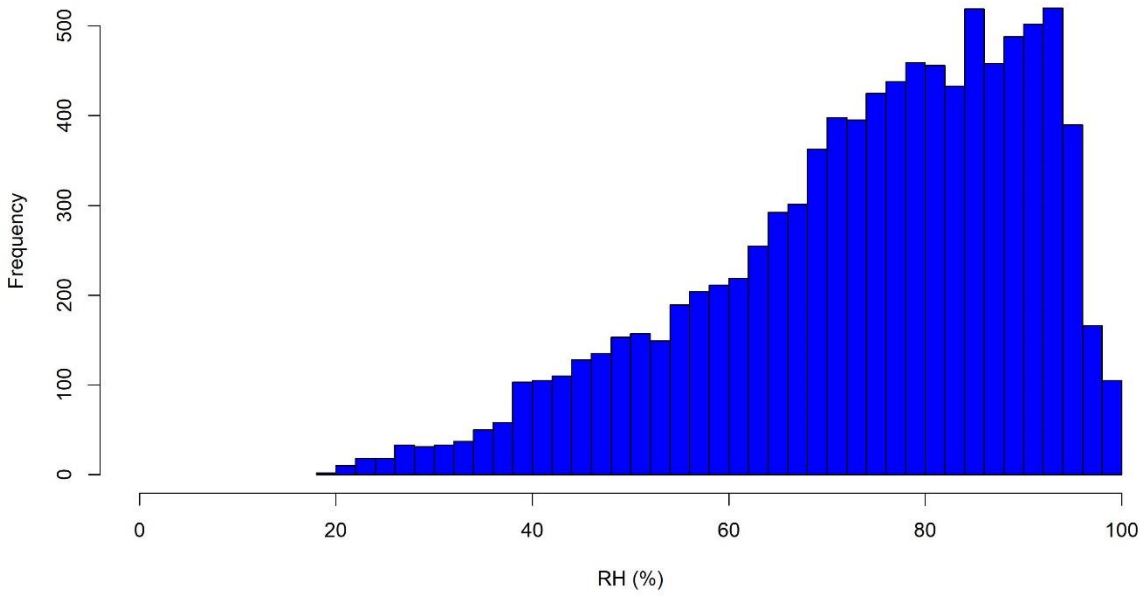


Figure 6: Histogram of hourly relative humidities (%) during the field campaign

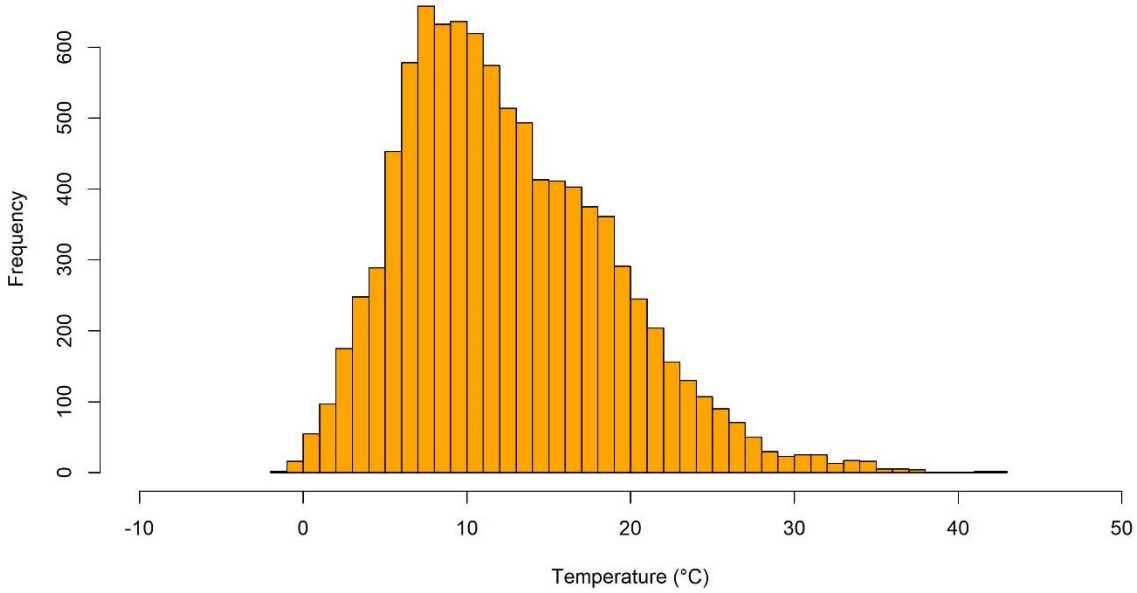


Figure 7: Histogram of hourly temperatures (°C) during the field campaign

Figure 8 shows the time plot and figure 9 the histogram of the hourly O_3 values measured with the reference instrument. Most O_3 hourly values are well below 100 µg/m^3. No hourly values higher than 200 µg/m^3 occurred. The average O_3concentration during the field campaign was 38.7 µg/m^3. During the calibration period and evaluation period the average O_3 concentration was 41.6 µg/m^{3}and 38.4 µg/m^3 respectively.

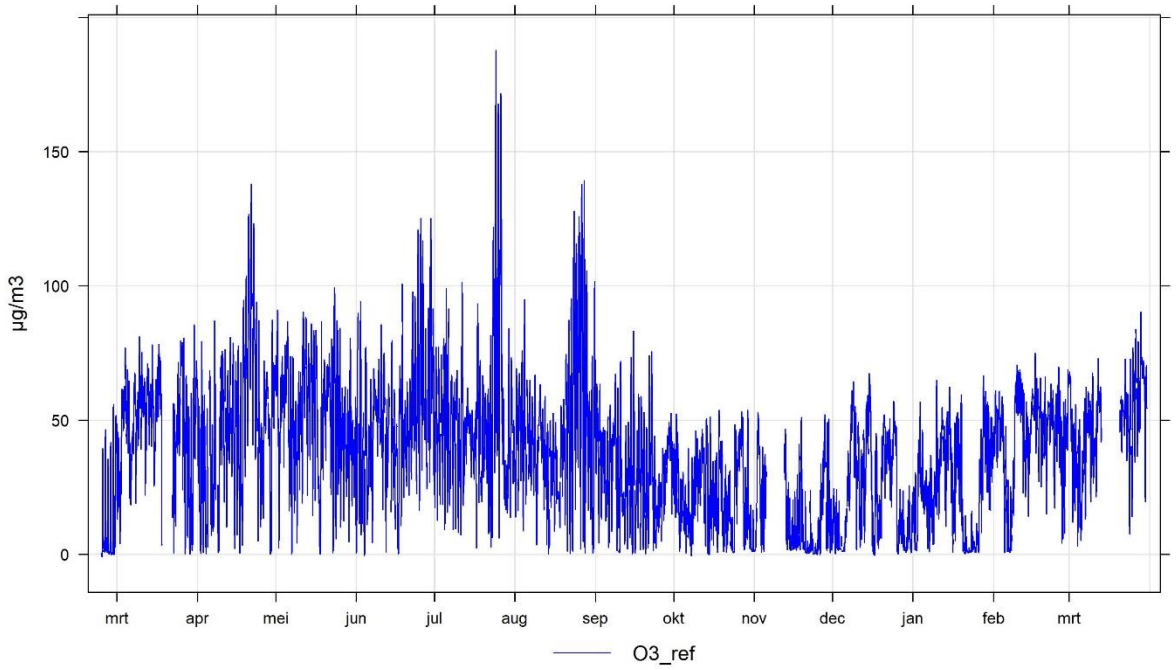


Figure 8: Time plot of hourly O_3 values (µg/m³) measured with a reference instrument during the field campaign.

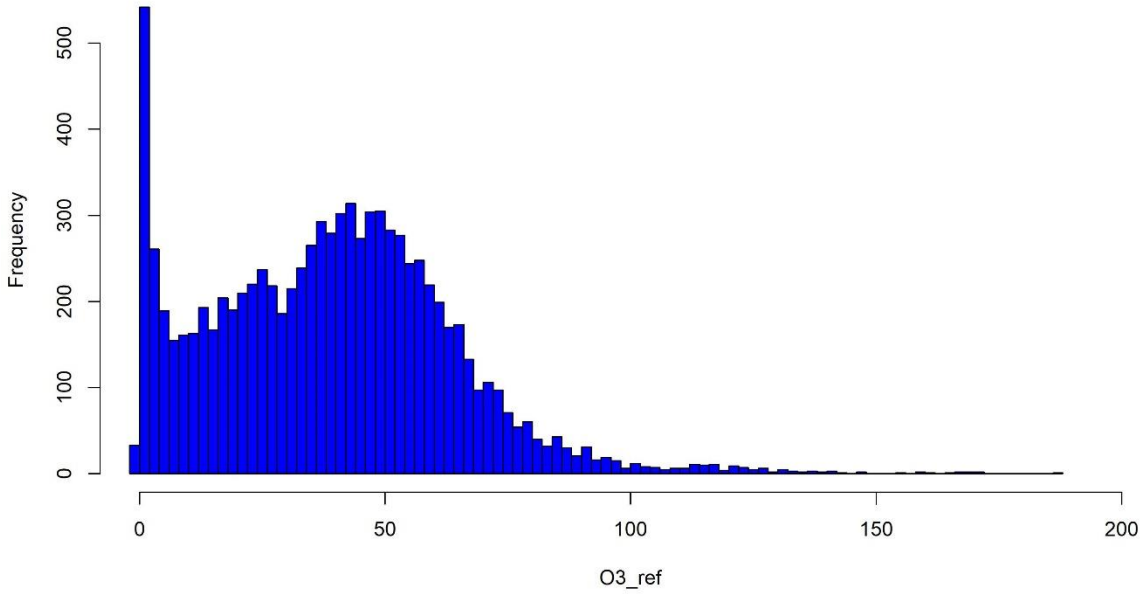


Figure 9: Histogram of hourly O_3 concentrations (µg/m³) measured with a reference instrument during the field campaign

Although the average temperature and O_3 were rather similar during the calibration period and validation period, we hardly measured hourly temperatures higher than 20 °C or O_3 concentrations higher than 100 µg/m^3 during the calibration period. In summertime these values are frequently exceeded. The choice of the calibration period from February 23, 2019 until March 31, 2019 compared to a calibration period of another length or in another season can affect the calibration functions. The investigation of the effect of the calibration period is considered outside the aim of the project.

Field Evaluation
Alphasense B43F NO_2 sensor

Manufacturer: Alphasense

Link to website manufacturer

Link to test protocol

3 Alphasense B43F NO_2 sensor

3.1 Validation and data coverage

A lot of negative values occur in the raw sensor data. These negative values are present on the same moments for all the sensors, as can be seen on the figure below. Therefore these peaks were not removed. Besides these negative values, both negative and positive peaks occur. When these peaks occurred after a restart of the measurements, they were marked as invalid. Other peaks were marked as suspicious when they were remarkable higher or lower than the values of the other sensors. When negative and positive peaks occurred after each other, both were removed.

The sensor VQH0 stopped measuring March 19, 2020.

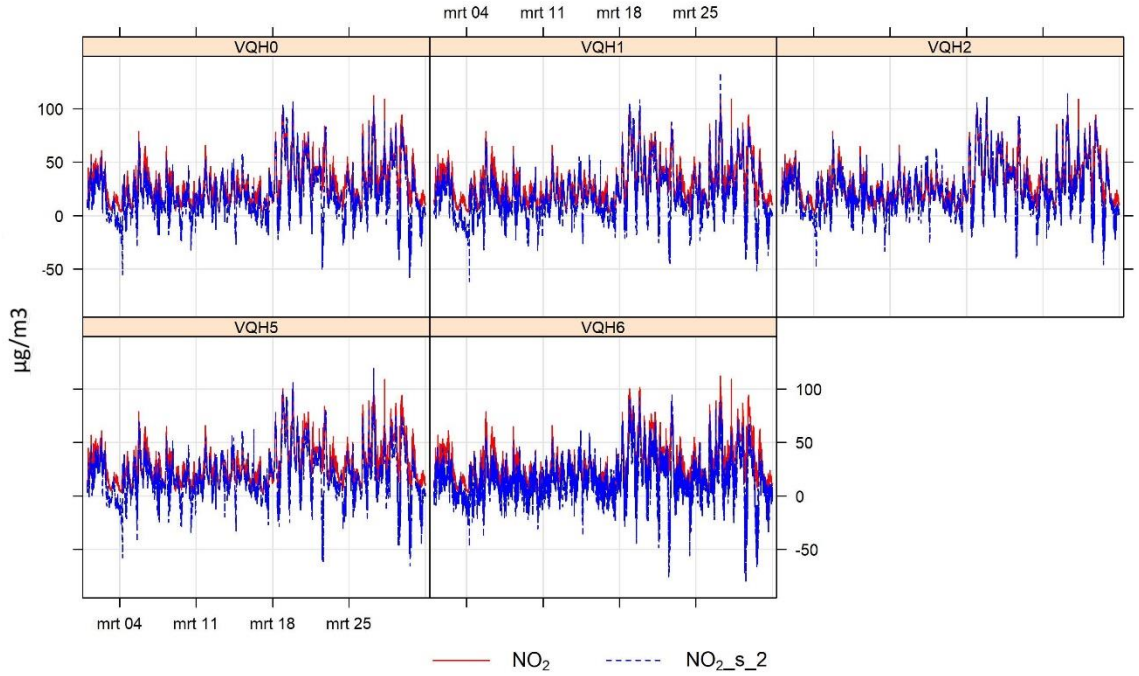


Figure 10: Alphasense B43F NO_2 sensor: Five minute values of the five sensor units in March 2020

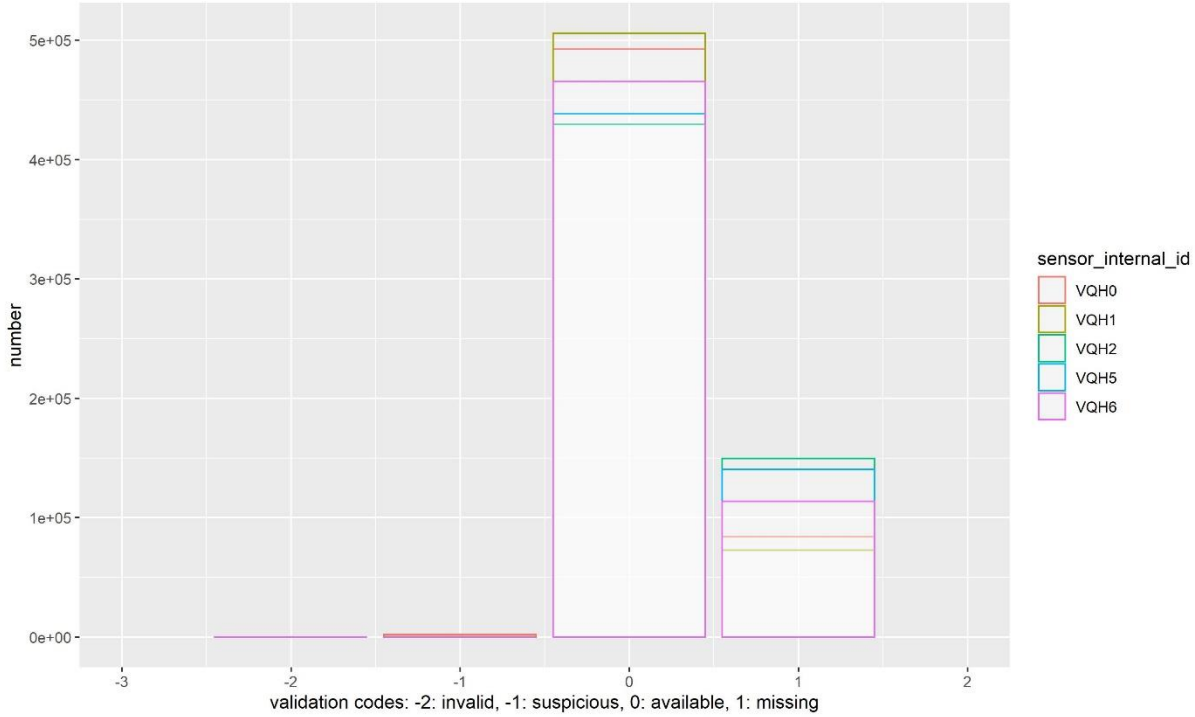


Figure 11: Alphasense B43F NO_2 sensor: Number sensor minute values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 3: Alphasense B43F NO_2 sensor: Number sensor minute values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQH0	36	2088	492750	84006	85
VQH1	39	441	505787	72613	87
VQH2	77	83	429260	149460	74
VQH5	142	2	438482	140254	76
VQH6	79	16	465161	113624	80

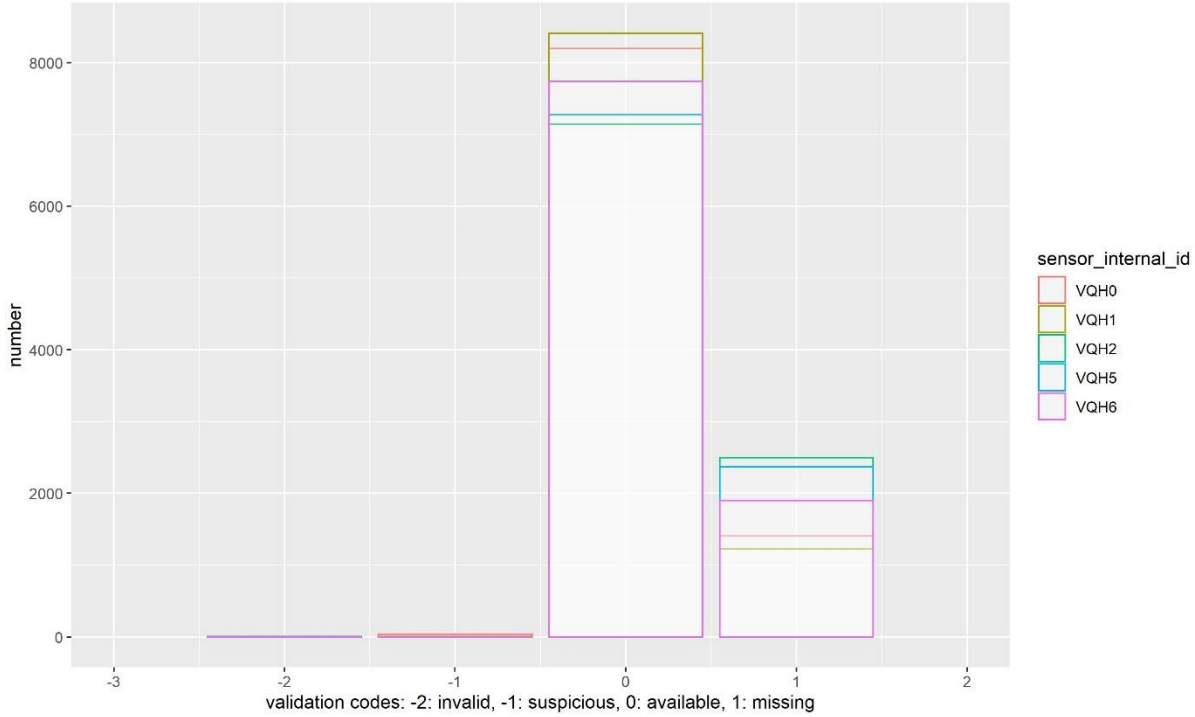


Figure 12: Alphasense B43F NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 4: Alphasense B43F NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQH0	1	41	8197	1409	85
VQH1	1	8	8410	1229	87
VQH2	2	2	7147	2497	74
VQH5	3	0	7275	2370	75
VQH6	2	0	7742	1904	80

3.2 Uncalibrated sensor data and sensor data calibrated with parameters from linear regression

3.2.1 Calibration parameters

Table 5: Alphasense B43F NO_2 sensor: Parameters from linear regression against reference method - hourly field data from February 23 2019 - March 31 2019

sensor_internal_id	slope	intercept
VQH0	1.10	-14.1
VQH1	1.13	-17.8
VQH2	1.07	-9.8
VQH5	1.08	-15.2
VQH6	0.84	-12.7

3.2.2 Comparison sensor versus reference

3.2.2.1 Time plot and scatter plots of hourly values

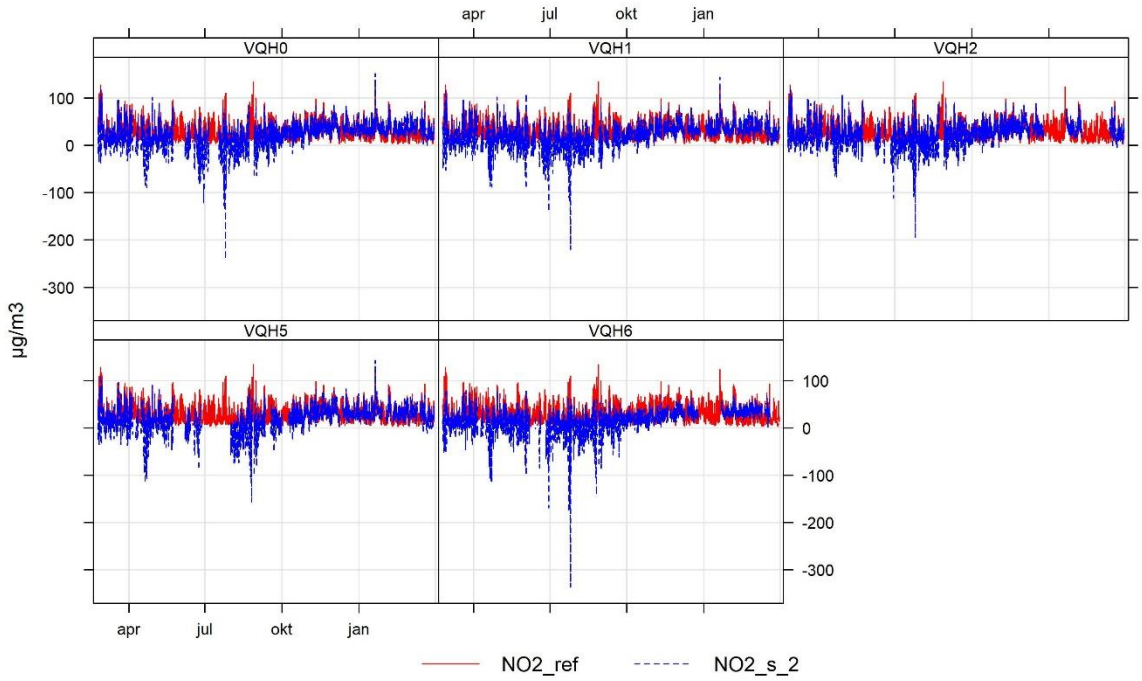


Figure 13: Alphasense B43F NO_2 sensor: Time plot uncalibrated sensor hourly values and reference values (µg/m³)

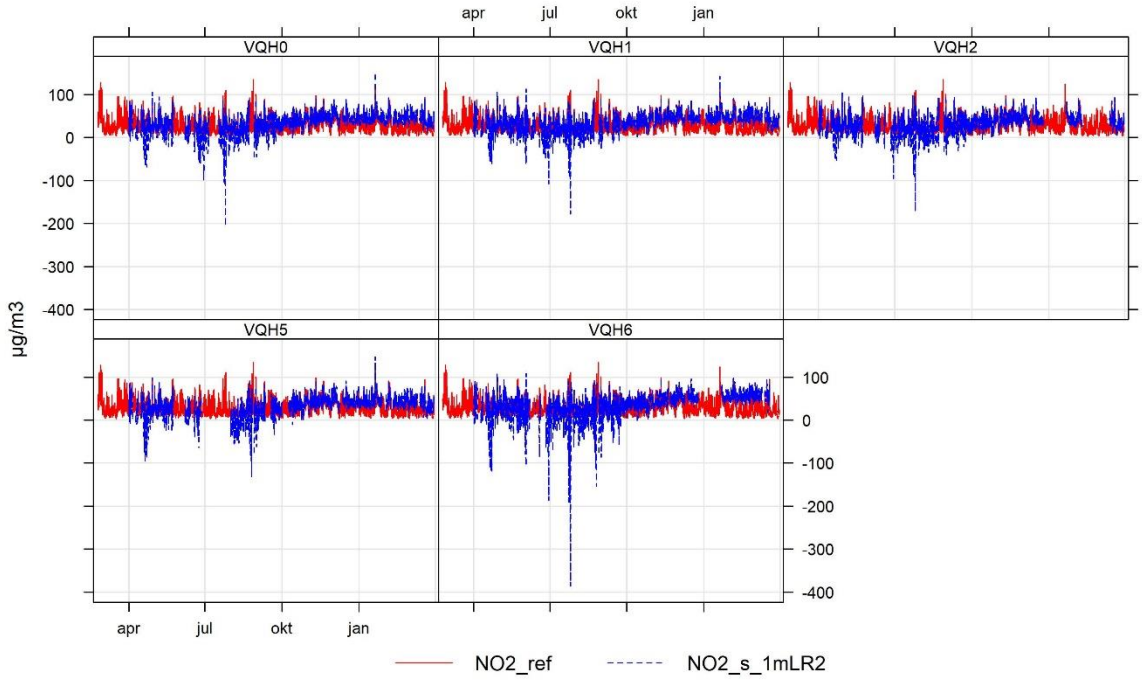


Figure 14: Alphasense B43F NO_2 sensor: Time plot of sensor hourly values calibrated with the linear regression parameters and reference values (µg/m³)

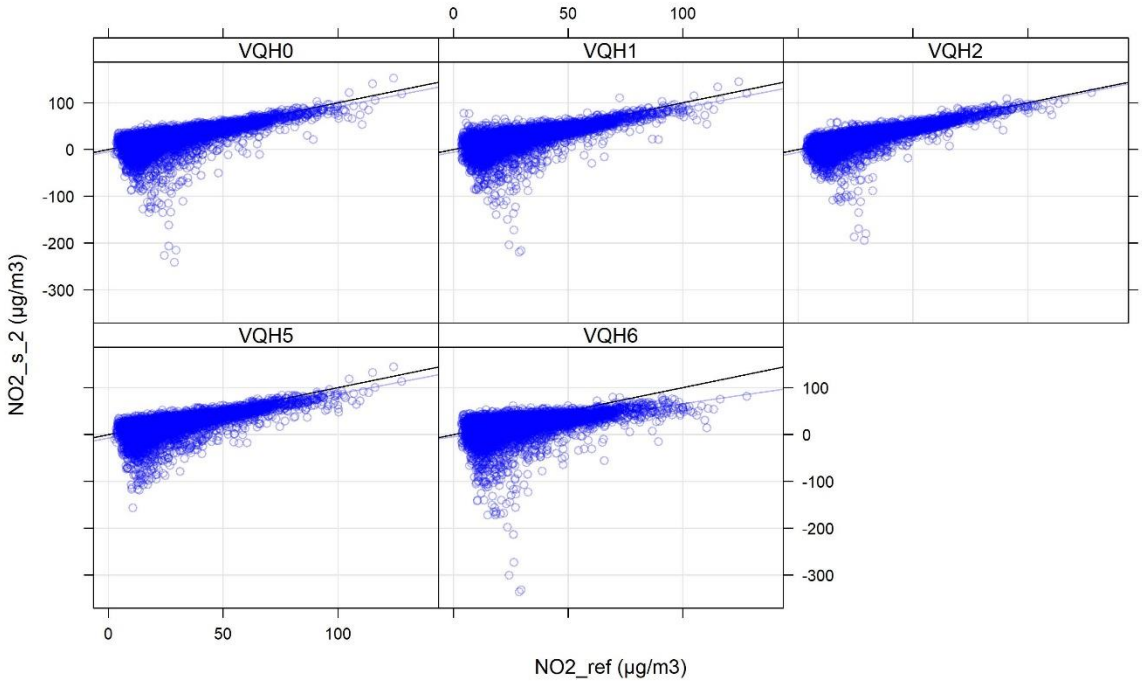


Figure 15: Alphasense B43F NO_2 sensor: Scatter plot of uncalibrated sensor hourly values versus reference values (µg/m³)

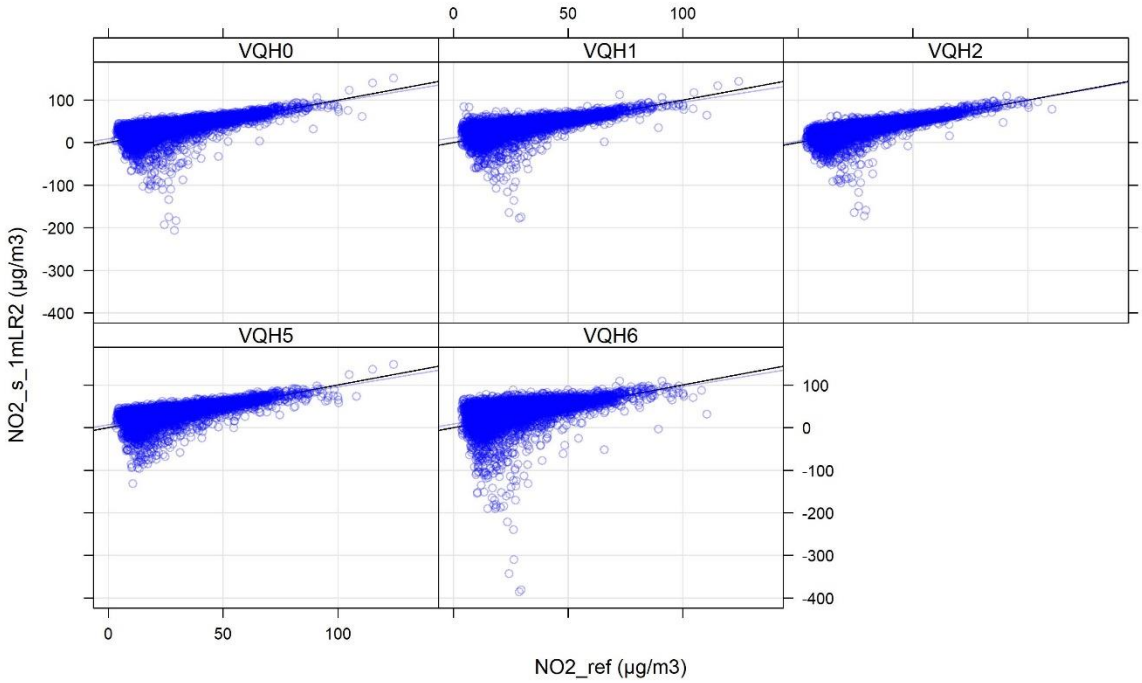


Figure 16: Alphasense B43F NO_2 sensor: Scatter plot sensor hourly values calibrated with the linear regression parameters versus reference values (µg/m³)

3.2.2.2 Ratio of hourly sensor values versus reference values

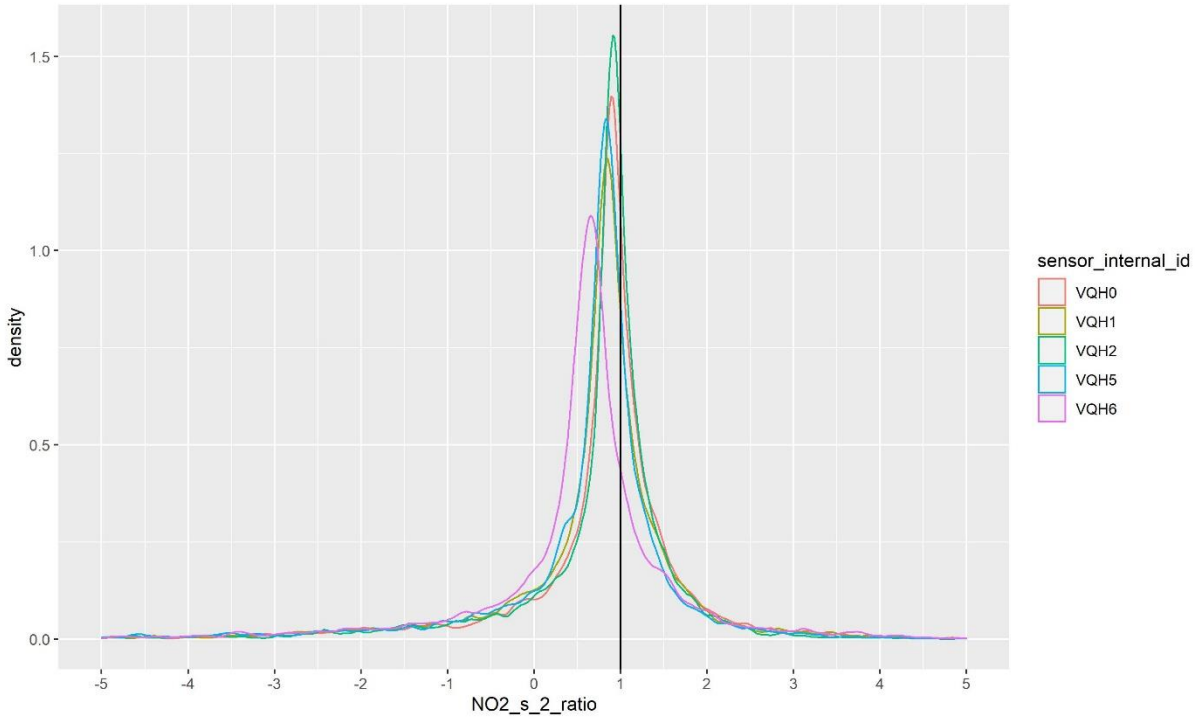


Figure 17: Alphasense B43F NO_2 sensor: Density plot of uncalibrated ratio sensor hourly values versus reference values

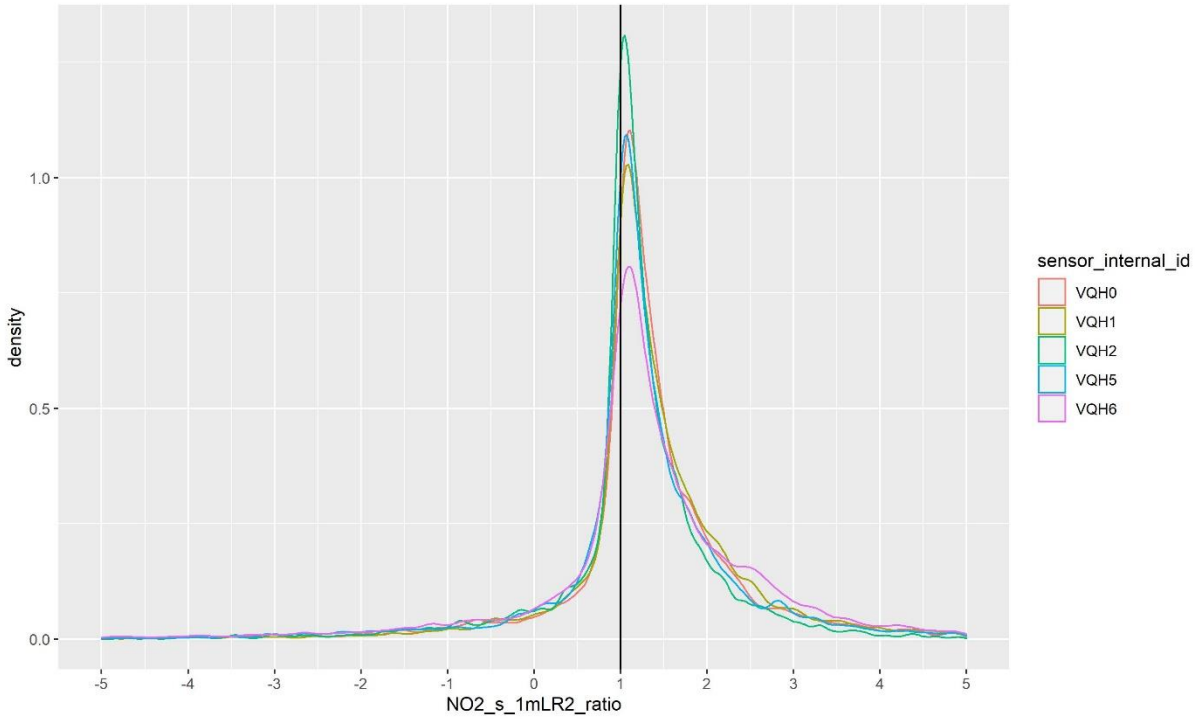


Figure 18: Alphasense B43F NO_2 sensor: Density plot of ratio sensor hourly values calibrated with the linear regression parameters versus reference values

3.2.3 Influence of time, temperature, relative humidity and O_3

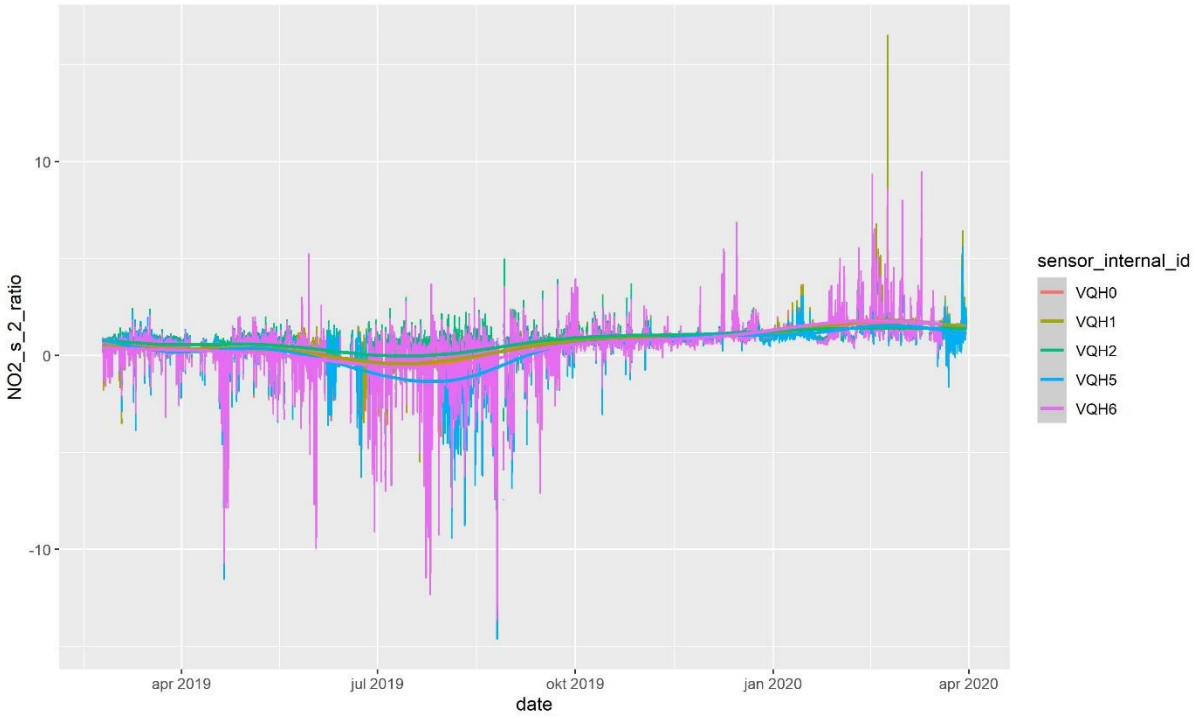


Figure 19: Alphasense B43F NO_2 sensor: Time plot ratio sensor hourly values versus reference values (µg/m³)

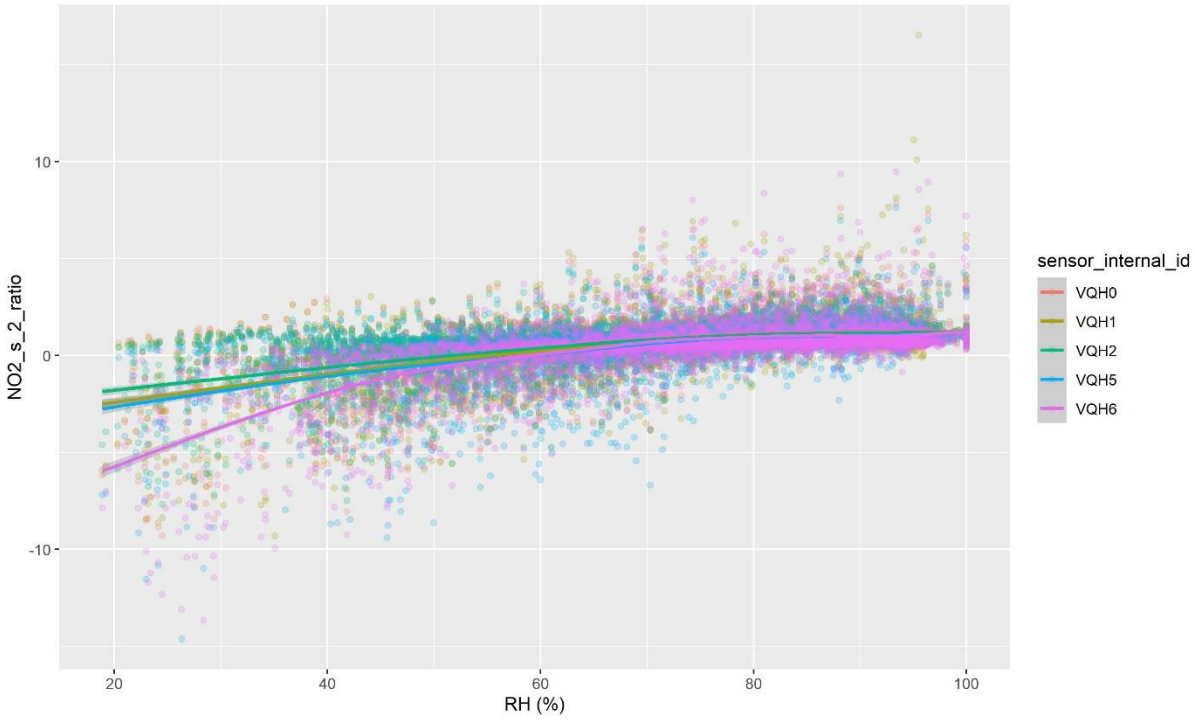


Figure 20: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to relative humidity (%)

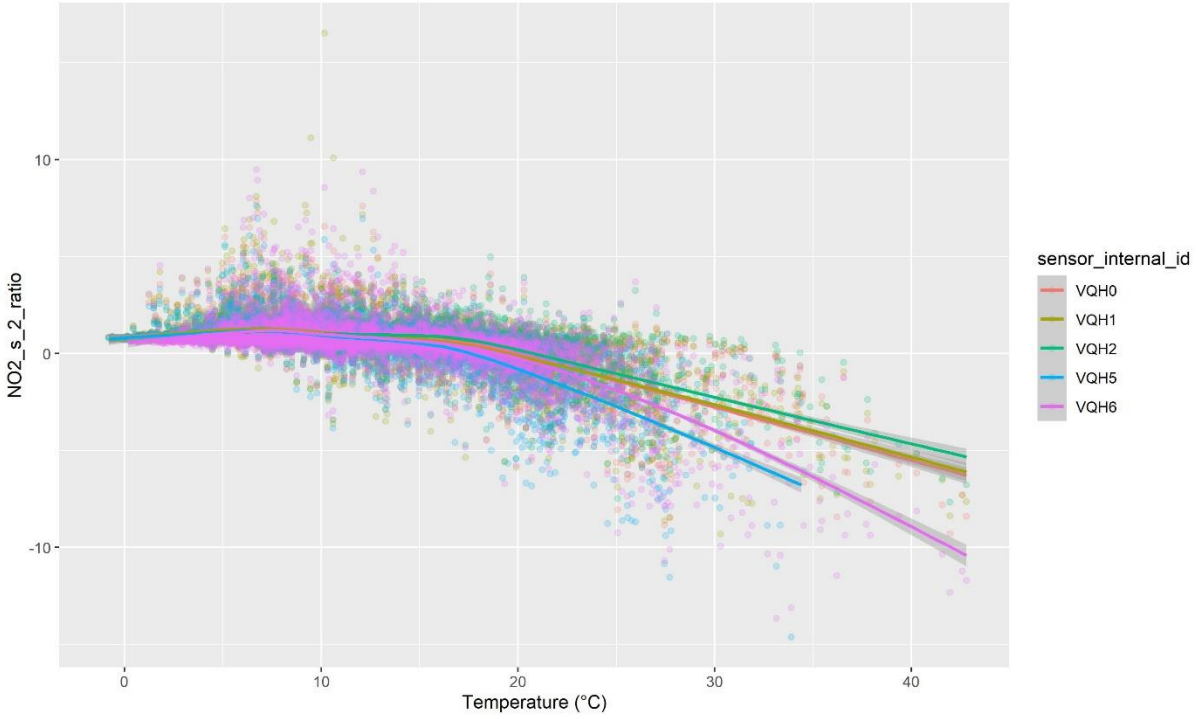


Figure 21: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to temperature (°C)

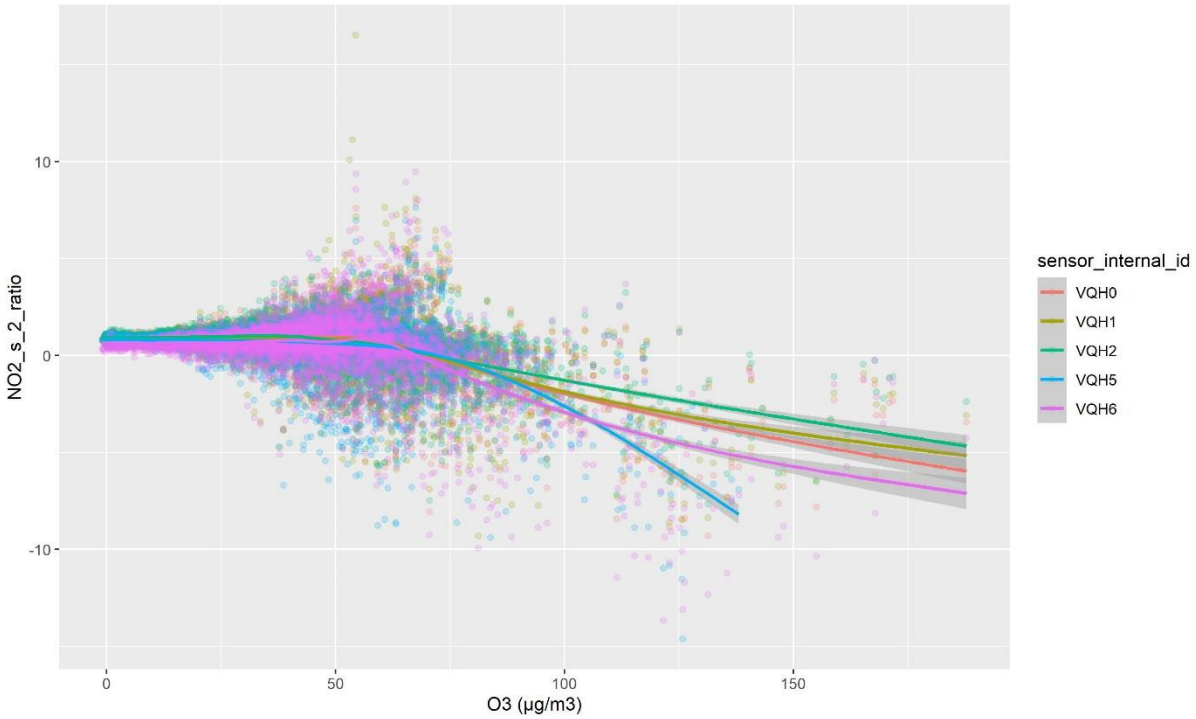


Figure 22: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to O_3 ($\mu g/m^3$)

3.2.4 Descriptive parameters

Table 6: Alphasense B43F NO_2 sensor: Descriptive parameters for uncalibrated sensors and sensors calibrated with the linear regression parameters. ID: sensor idea, n: number of values, R^2: coefficient of determination, U_{bs}: between sampler uncertainty

		Calibration		Evaluation				
	ID	n	R^2	n	mean bias ($\mu g/m^3$)	R^2	$u_{bs}(\mu g/m^3)$	u_{bs} (%)
NO_2_s_2	VQH0			7743	-6.08	0.46		
NO_2_s_2	VQH1			7953	-7.30	0.46		
NO_2_s_2	VQH2			6744	-5.38	0.58		
NO_2_s_2	VQH5			6869	-9.53	0.47		
NO_2_s_2	VQH6			7312	-13.50	0.23		
NO_2_s_2	all sensors			36621			19.38	90.61
NO_2_s_1mLR2	VQH0	845	0.79	6898	5.12	0.42		
NO_2_s_1mLR2	VQH1	846	0.75	7107	6.51	0.43		
NO_2_s_1mLR2	VQH2	846	0.85	5898	2.47	0.53		
NO_2_s_1mLR2	VQH5	846	0.73	6023	3.53	0.44		
NO_2_s_1mLR2	VQH6	846	0.52	6466	5.37	0.21		
NO_2_s_1mLR2	all sensors			32392			18.99	56.35

3.2.5 Relative expanded uncertainty

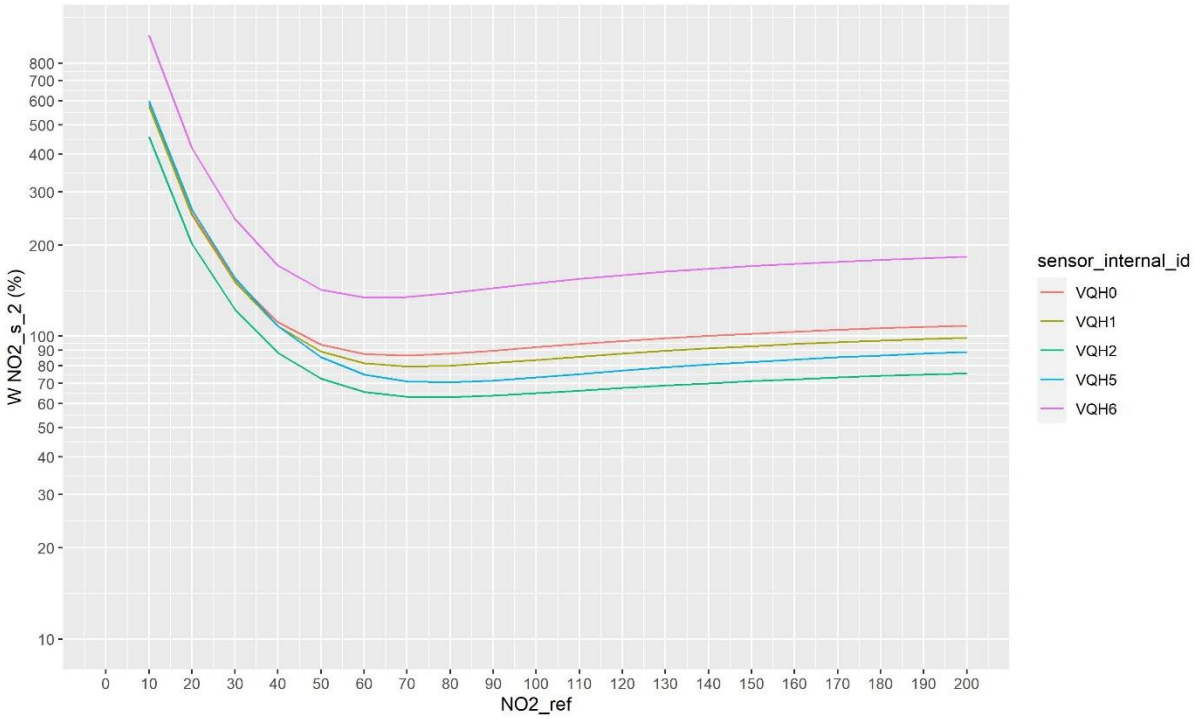


Figure 23: Alphasense B43F NO_2 sensor: Relative expanded uncertainty (W (%)) for uncalibrated sensor values according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³

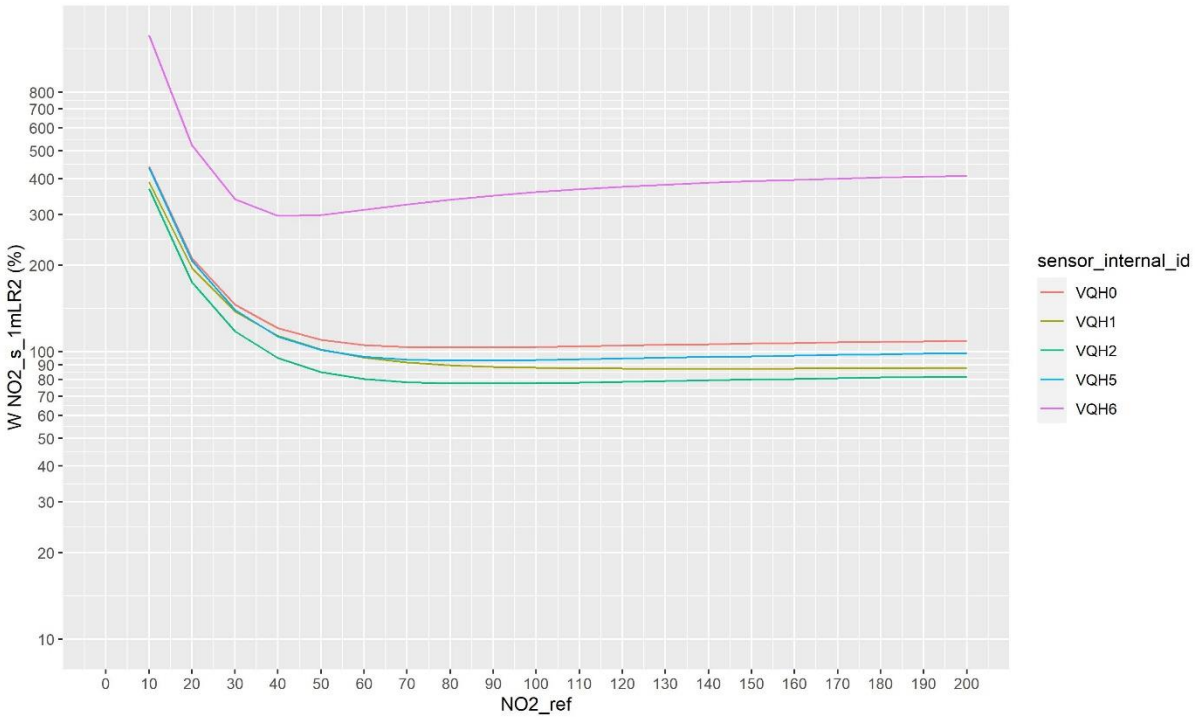


Figure 24: Alphasense B43F NO_2 sensor: Relative expanded uncertainty (W (%)) for sensor values calibrated with the linear regression parameters according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³

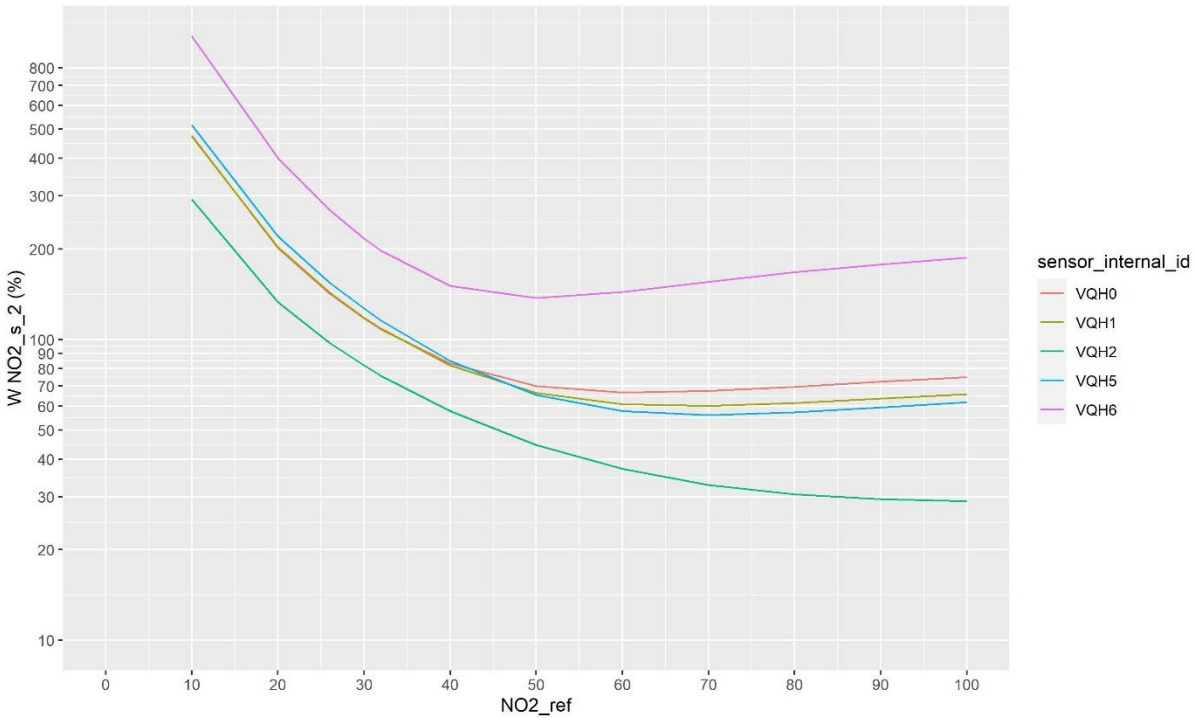


Figure 25: Alphasense B43F NO_2 sensor: Relative expanded uncertainty (W (%)) for uncalibrated sensor values according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³

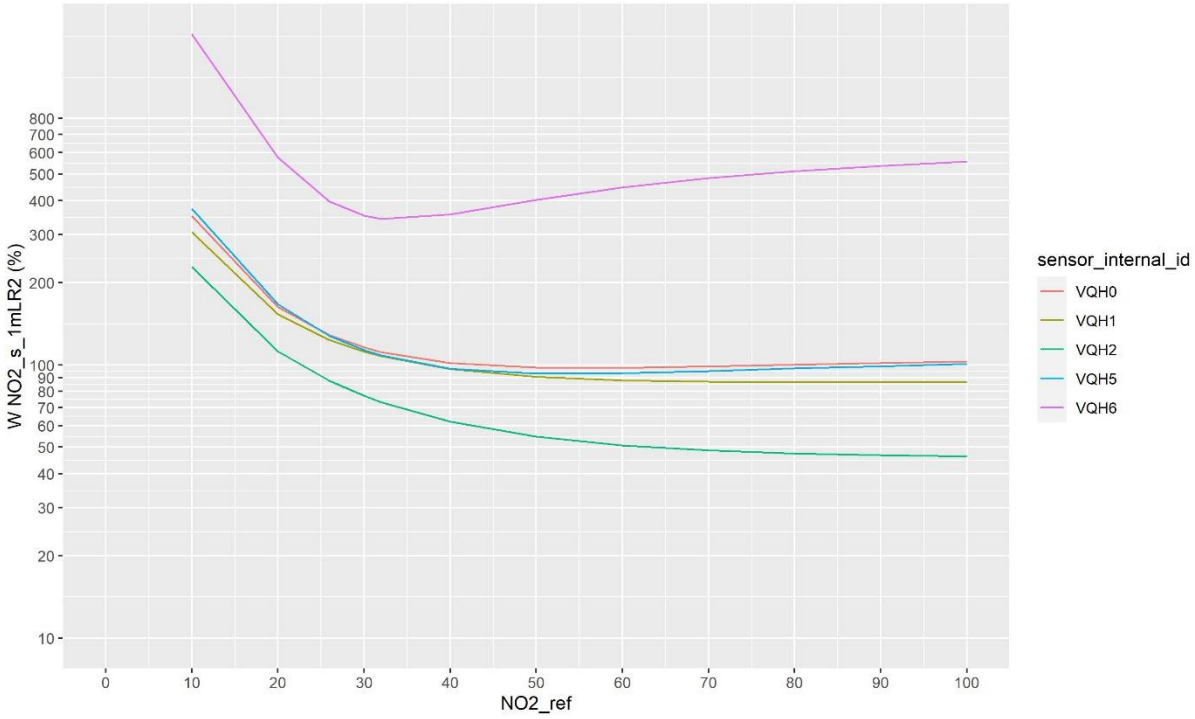


Figure 26: Alphasense B43F NO_2 sensor: Relative expanded uncertainty (W (%)) for sensor values calibrated with the linear regression parameters according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³

Table 7: Alphasense B43F NO_2 sensor: Relative expanded uncertainty for uncalibrated sensors (NO_2_S_2) and for sensors calibrated with the linear regression parameters (NO_2_S_1mLR2) according to Guidance of Equivalence calculated at NO_2 hourly reference concentrations of 100 µg/m³ (LAT), 140 µg/m³ (UAT) and 200 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_2	VQH0	100	22.31	40.26	92.07
NO_2_s_2	VQH1	100	21.62	35.78	83.61
NO_2_s_2	VQH2	100	17.66	27.19	64.85
NO_2_s_2	VQH5	100	21.27	29.76	73.16
NO_2_s_2	VQH6	100	34.26	66.57	149.74
NO_2_s_1mLR2	VQH0	100	21.14	47.41	103.81
NO_2_s_1mLR2	VQH1	100	19.37	39.44	87.88
NO_2_s_1mLR2	VQH2	100	17.41	34.76	77.75
NO_2_s_1mLR2	VQH5	100	20.63	41.99	93.57
NO_2_s_1mLR2	VQH6	100	50.12	172.35	358.98
NO_2_s_2	VQH0	140	22.31	66.66	100.42
NO_2_s_2	VQH1	140	21.62	60.11	91.26
NO_2_s_2	VQH2	140	17.66	45.70	69.99
NO_2_s_2	VQH5	140	21.27	52.33	80.69
NO_2_s_2	VQH6	140	34.26	111.96	167.26
NO_2_s_1mLR2	VQH0	140	21.14	71.26	106.18
NO_2_s_1mLR2	VQH1	140	19.37	57.85	87.15
NO_2_s_1mLR2	VQH2	140	17.41	52.89	79.54
NO_2_s_1mLR2	VQH5	140	20.63	63.85	95.86
NO_2_s_1mLR2	VQH6	140	50.12	265.93	386.59
NO_2_s_2	VQH0	200	22.31	106.25	108.57
NO_2_s_2	VQH1	200	21.62	96.62	99.01
NO_2_s_2	VQH2	200	17.66	73.46	75.56
NO_2_s_2	VQH5	200	21.27	86.17	88.76
NO_2_s_2	VQH6	200	34.26	180.03	183.26
NO_2_s_1mLR2	VQH0	200	21.14	107.03	109.10
NO_2_s_1mLR2	VQH1	200	19.37	85.46	87.63
NO_2_s_1mLR2	VQH2	200	17.41	80.08	81.95
NO_2_s_1mLR2	VQH5	200	20.63	96.65	98.82
NO_2_s_1mLR2	VQH6	200	50.12	406.31	409.39

Table 8: Alphasense B43F NO_2 sensor: Relative expanded uncertainty for uncalibrated sensors (NO_2_S_2) and for sensors calibrated with the linear regression parameters (NO_2_S_1mLR2) according to Guidance of Equivalence calculated at NO_2 daily reference concentrations of 26 µg/m³ (LAT), 32 µg/m³ (UAT) and 40 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_2	VQH0	26	16.63	-8.06	142.13
NO_2_s_2	VQH1	26	16.29	-9.03	143.26
NO_2_s_2	VQH2	26	11.08	-6.15	97.47
NO_2_s_2	VQH5	26	16.33	-11.74	154.70
NO_2_s_2	VQH6	26	30.08	-18.09	269.98
NO_2_s_1mLR2	VQH0	26	16.35	3.48	128.60
NO_2_s_1mLR2	VQH1	26	15.17	5.31	123.64
NO_2_s_1mLR2	VQH2	26	11.22	1.85	87.43
NO_2_s_1mLR2	VQH5	26	16.55	1.38	127.76
NO_2_s_1mLR2	VQH6	26	51.49	-3.20	396.85
NO_2_s_2	VQH0	32	16.63	-4.68	107.96
NO_2_s_2	VQH1	32	16.29	-5.98	108.44
NO_2_s_2	VQH2	32	11.08	-4.89	75.69
NO_2_s_2	VQH5	32	16.33	-8.65	115.52
NO_2_s_2	VQH6	32	30.08	-9.44	197.03
NO_2_s_1mLR2	VQH0	32	16.35	7.16	111.57
NO_2_s_1mLR2	VQH1	32	15.17	8.18	107.72
NO_2_s_1mLR2	VQH2	32	11.22	3.34	73.14
NO_2_s_1mLR2	VQH5	32	16.55	5.13	108.31
NO_2_s_1mLR2	VQH6	32	51.49	19.20	343.47
NO_2_s_2	VQH0	40	16.63	-0.18	83.15
NO_2_s_2	VQH1	40	16.29	-1.91	82.00
NO_2_s_2	VQH2	40	11.08	-3.22	57.68
NO_2_s_2	VQH5	40	16.33	-4.55	84.76
NO_2_s_2	VQH6	40	30.08	2.09	150.75
NO_2_s_1mLR2	VQH0	40	16.35	12.07	101.63
NO_2_s_1mLR2	VQH1	40	15.17	12.00	96.73
NO_2_s_1mLR2	VQH2	40	11.22	5.34	62.10
NO_2_s_1mLR2	VQH5	40	16.55	10.14	97.05
NO_2_s_1mLR2	VQH6	40	51.49	49.08	355.66

Table 9: Alphasense B43F NO_2 sensor: Parameters of orthogonal regression of hourly and daily sensor data versus reference NO_2 for uncalibrated sensors (NO2_S_2) and for sensors calibrated with the linear regression parameters (NO2_S_1mLR2)

		hourly values		daily values	
	ID	slope	intercept (µg/m³)	slope	intercept (µg/m³)
NO_2_s_2	VQH0	1.66	-25.72	1.56	-22.69
NO_2_s_2	VQH1	1.61	-25.06	1.51	-22.26
NO_2_s_2	VQH2	1.46	-19.08	1.21	-11.59
NO_2_s_2	VQH5	1.56	-26.64	1.51	-25.09
NO_2_s_2	VQH6	2.13	-46.88	2.44	-55.56
NO_2_s_1mLR2	VQH0	1.60	-12.21	1.61	-12.48
NO_2_s_1mLR2	VQH1	1.46	-6.58	1.48	-7.12
NO_2_s_1mLR2	VQH2	1.45	-10.56	1.25	-4.63
NO_2_s_1mLR2	VQH5	1.55	-12.66	1.63	-14.88
NO_2_s_1mLR2	VQH6	3.34	-61.60	4.73	-100.29

3.2.6 Conclusions

A lot of negative values occur in the uncalibrated sensor data. These negative values occur mostly in the first half of the campaign, roughly until the end of September 2019. Therefore, the ratios of the sensor data versus the reference method are often negative in the first half of the campaign but most of the time positive in the second half. The most negative ratios against the reference method occur with high temperatures, low relative humidity and high O_3 concentrations.

As there are a lot of negative values in the sensor data, the mean biases of uncalibrated sensor data (*NO2_s_2*) versus the reference data are negative (between -14 and – 5 µg/m^3) for all the sensors. The R^2 varies between 0.46 and 0.58 for the sensors VQH0, VQH1, VQH2 and VQH5. VQH6 shows a lower correlation with the reference method (R^2 = 0.23). When we look at the expanded uncertainty of the hourly sensor data *NO2_s_2* at the LV (200 µg/m^3), the UAT (140 µg/m^3) and the LAT (100 µg/m^3), the expanded uncertainty is only ≤75 % at the LAT for sensors VQH2 and VQH5 and at the UAT for sensor VQH2. When we look at the expanded uncertainty of the daily sensor data *NO2_s_2* at the LV (40 µg/m), the UAT (32 µg/m^3) and the LAT (26 µg/m^3), the expanded uncertainty is only ≤ 75 % at the LV for sensor VQH2. There are no sensors for which the expanded uncertainties of the hourly or daily data are ≤ 25 % at the LV, the UAT and the LAT.

Calibration of the sensors with the parameters of the linear regression (*NO2_s_1mLR2*) improves the between sensor uncertainty in comparison with the uncalibrated sensor data (56 % versus 91 %). Calibration leads to positive mean biases in the sensor data in comparison with the reference method (between 2 and 7 µg/m^3). In general, the relative expanded uncertainty of the different sensors becomes larger. When we look at the expanded uncertainty of the hourly sensor data *NO2_s_1mLR2* at the LV, the UAT and the LAT, we see that the expanded uncertainty for not a single sensor is ≤ 75 %. When we look at the expanded uncertainty of the daily sensor data *NO2_s_1mLR2* at the LV, the UAT and the LAT, the expanded uncertainty is only ≤ 75 % at the UAT and LV for sensor VQH2. The expanded uncertainty at the LV, the UAT and the LAT for the hourly and daily sensor data *NO2_s_1mLR2* is always > 25 %.

3.3 Sensor data calibrated with parameters from multiple linear regression

3.3.1 Calibration parameters

Table 10: Alphasense B43F NO_2 sensor: Parameters from multiple linear regression (including NO_2 reference measurements (NO_2_ref), temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	T	RH
VQH0	-24.8	1.02	-1.64	0.41
VQH1	-21.7	1.02	-1.95	0.38
VQH2	-29.4	1.04	-0.76	0.39
VQH5	-22.1	0.97	-1.89	0.41
VQH6	-26.3	0.70	-1.64	0.48

Table 11: Alphasense B43F NO_2 sensor: Parameters from extended multiple linear regression (including NO_2 reference measurements (NO_2_ref), ozone reference measurements (O_3_ref) temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	O_3_ref	T	RH
VQH0	-42.5	1.16	0.15	-1.57	0.50
VQH1	-56.8	1.30	0.30	-1.83	0.54
VQH2	-54.3	1.22	0.21	-0.62	0.51
VQH5	-50.4	1.18	0.23	-1.74	0.55
VQH6	-73.5	1.05	0.40	-1.39	0.70

3.3.2 Comparison sensor versus reference

3.3.2.1 Time plot and scatter plots of hourly values

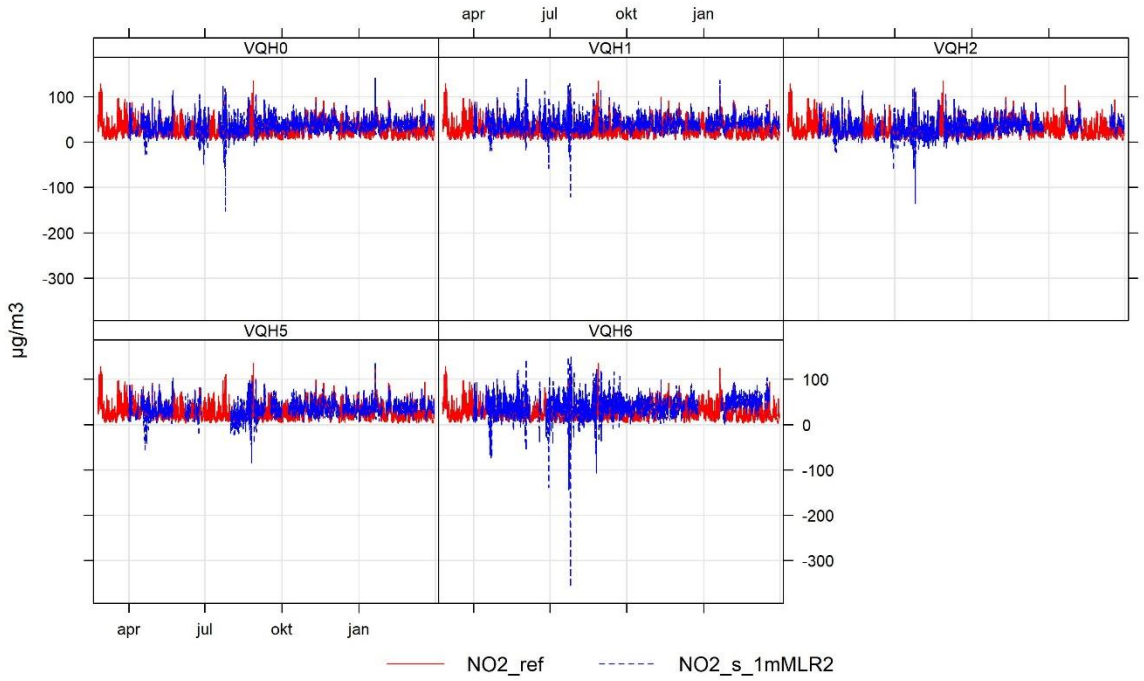


Figure 27: Alphasense B43F NO_2 sensor: Time plot of sensor hourly values calibrated with multiple linear regression model and reference values (µg/m³)

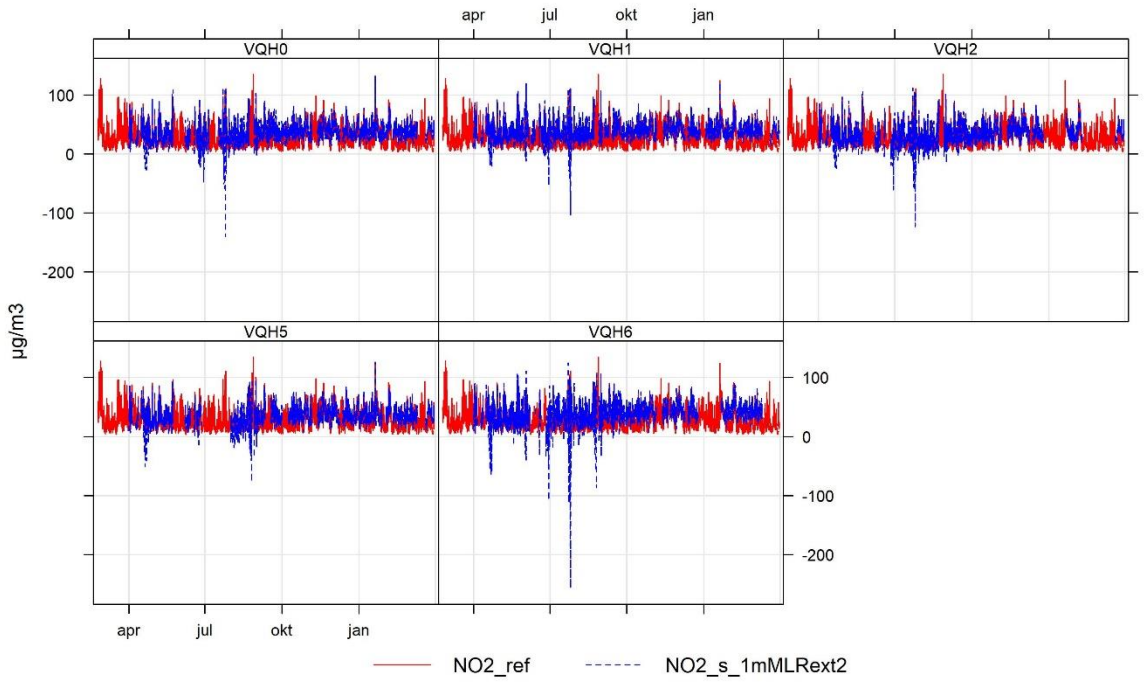


Figure 28: Alphasense B43F NO_2 sensor: Time plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

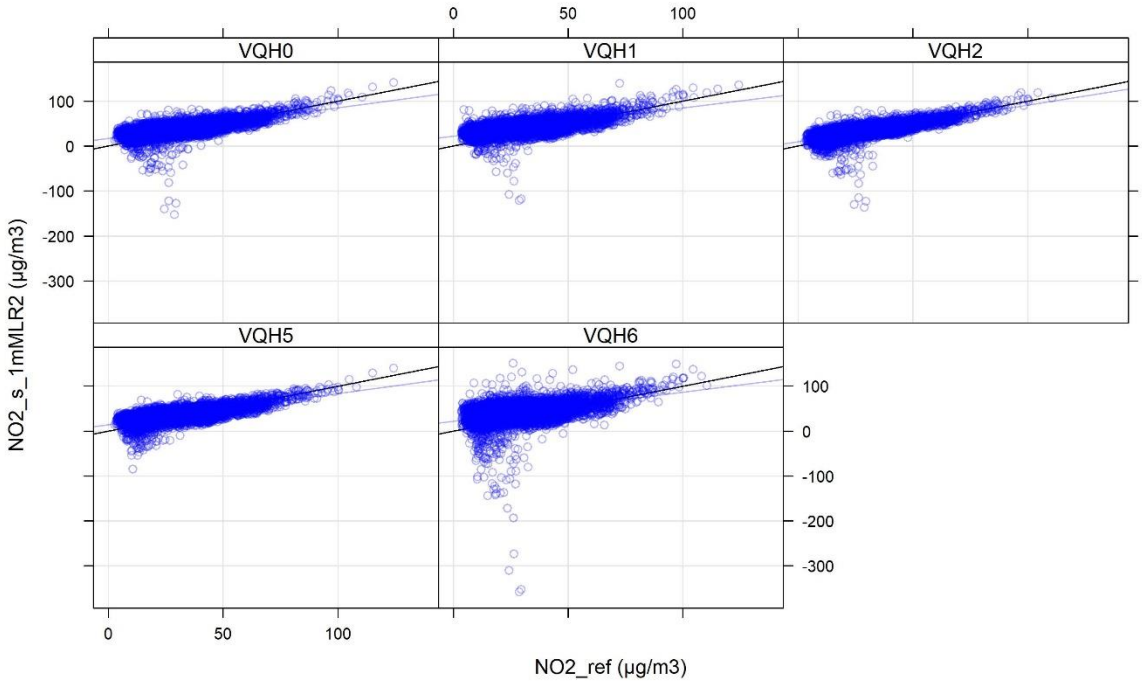


Figure 29: Alphasense B43F NO_2 sensor: Scatter plot of sensor hourly values calibrated with multiple linear regression model and reference values (µg/m³)

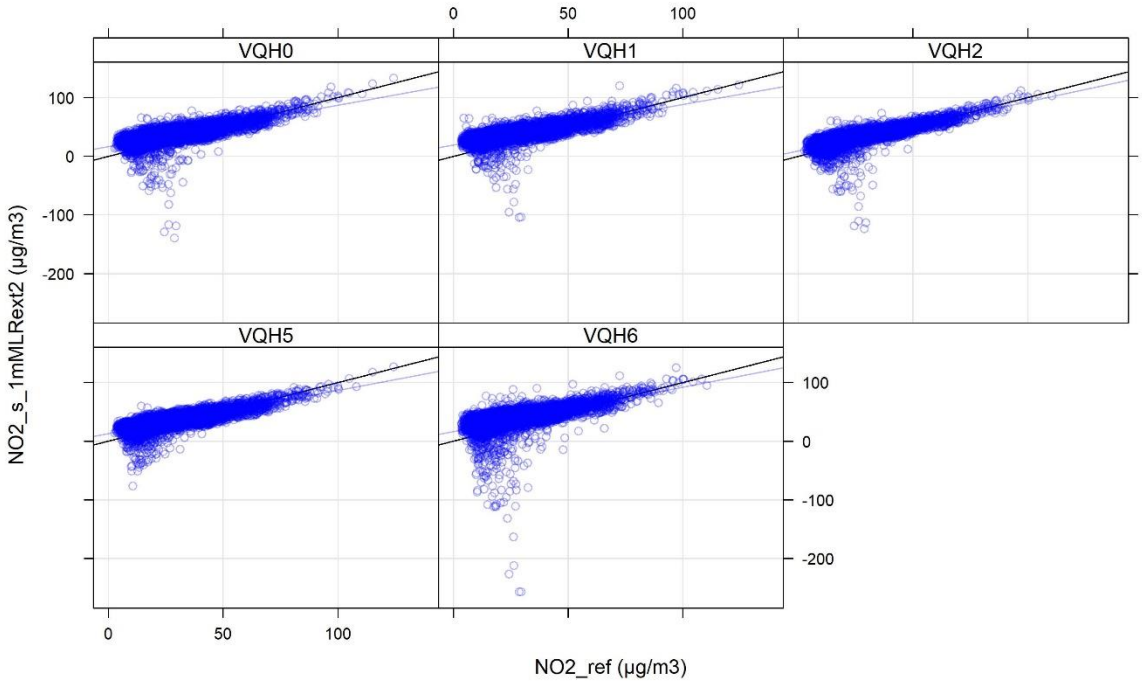


Figure 30: Alphasense B43F NO_2 sensor: Scatter plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

3.3.2.2 Ratio of hourly sensor values versus reference values

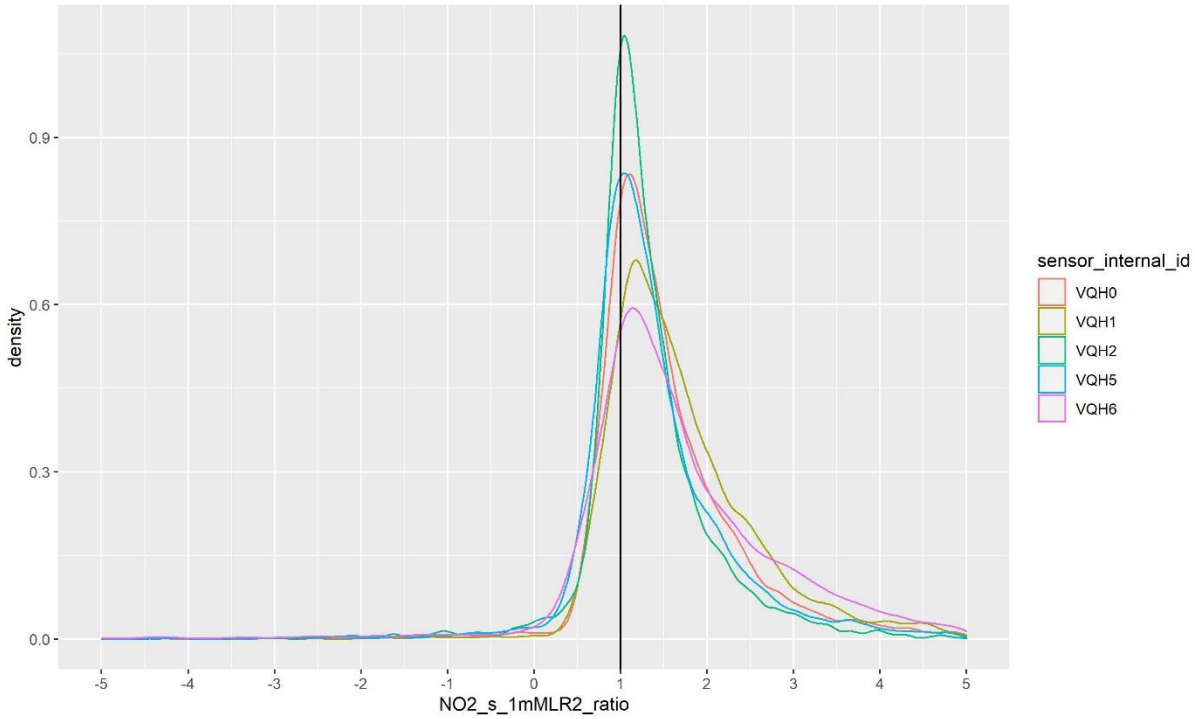


Figure 31: Alphasense B43F NO_2 sensor: Density plot of ratio sensor hourly values calibrated with multiple linear regression versus reference values

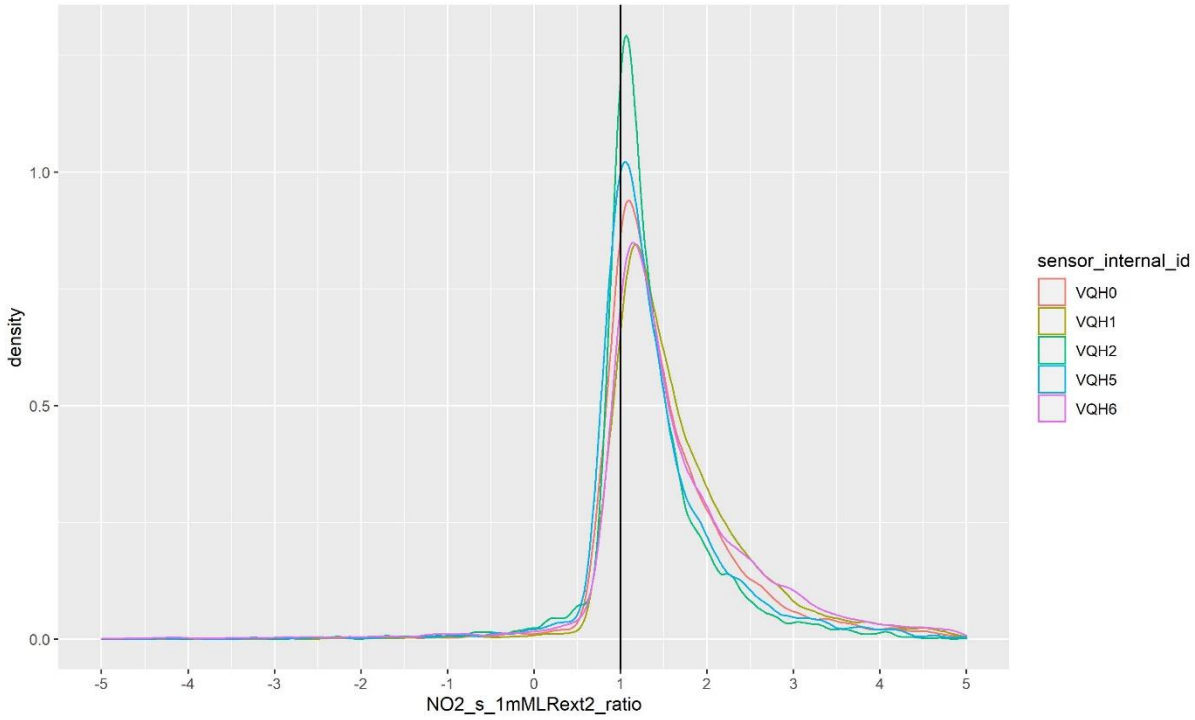


Figure 32: Alphasense B43F NO_2 sensor: Density plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values

3.3.3 Influence of time, temperature, relative humidity and O_3

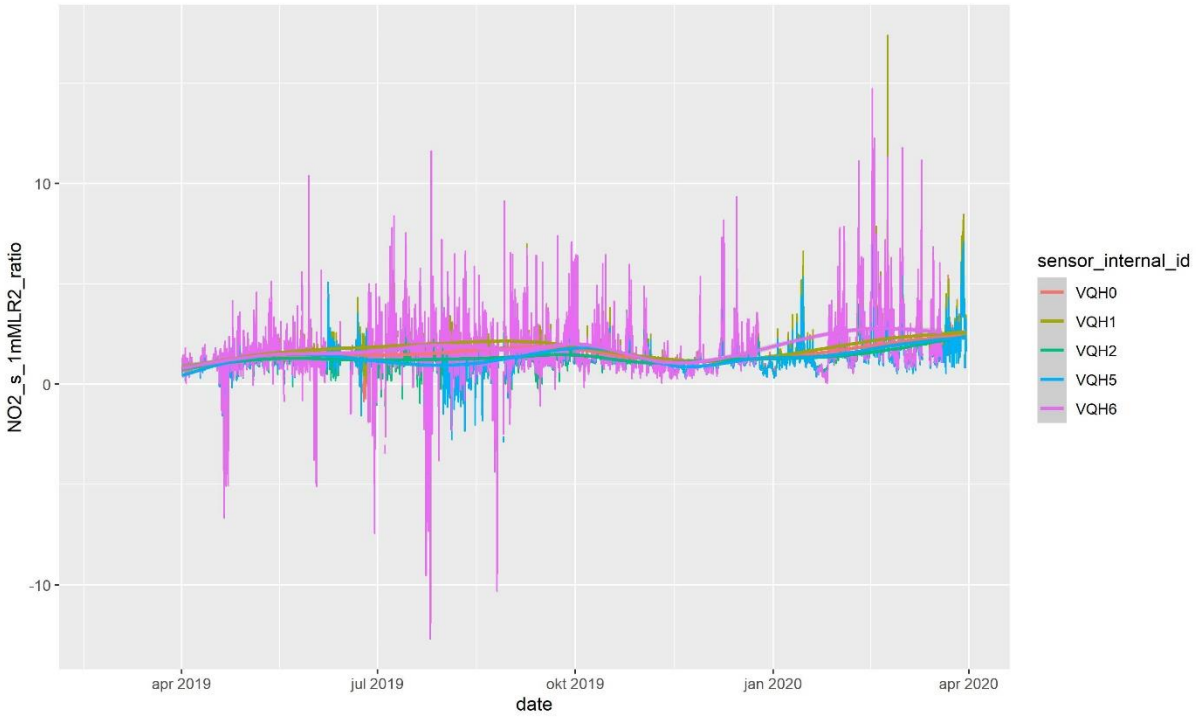


Figure 33: Alphasense B43F NO_2 sensor: Time plot of ratio sensor hourly values calibrated with multiple linear regression versus reference values (µg/m³)

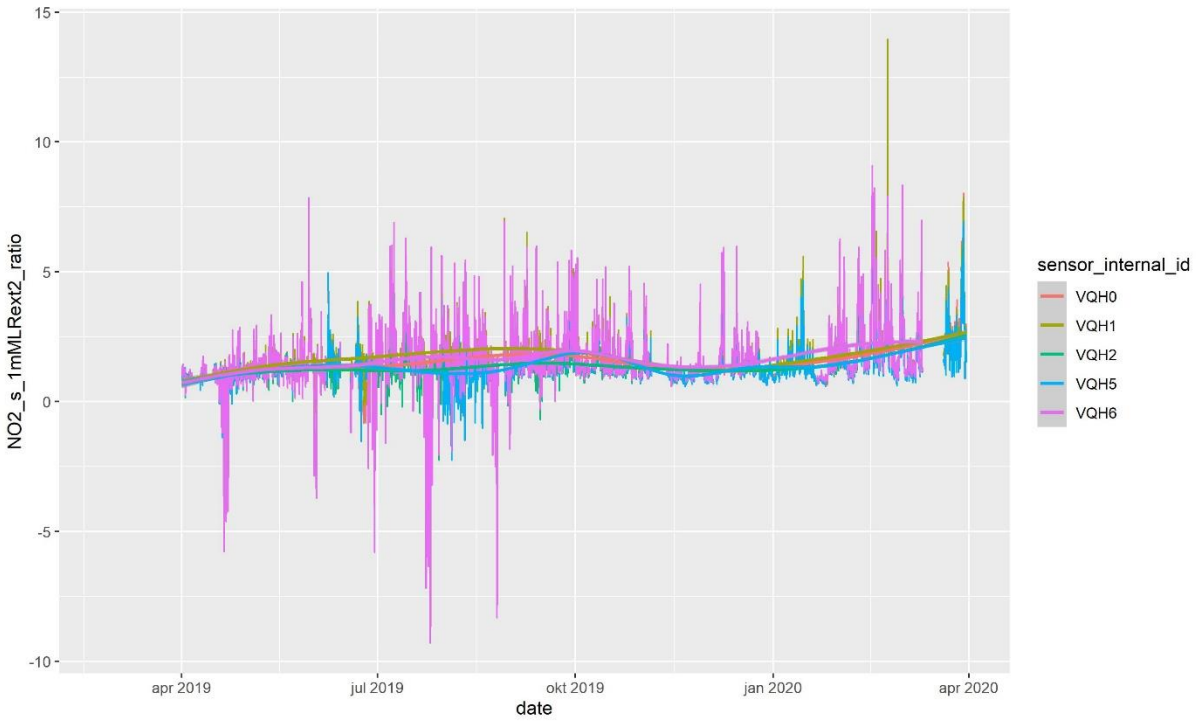


Figure 34: Alphasense B43F NO_2 sensor: Time plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values (µg/m³)

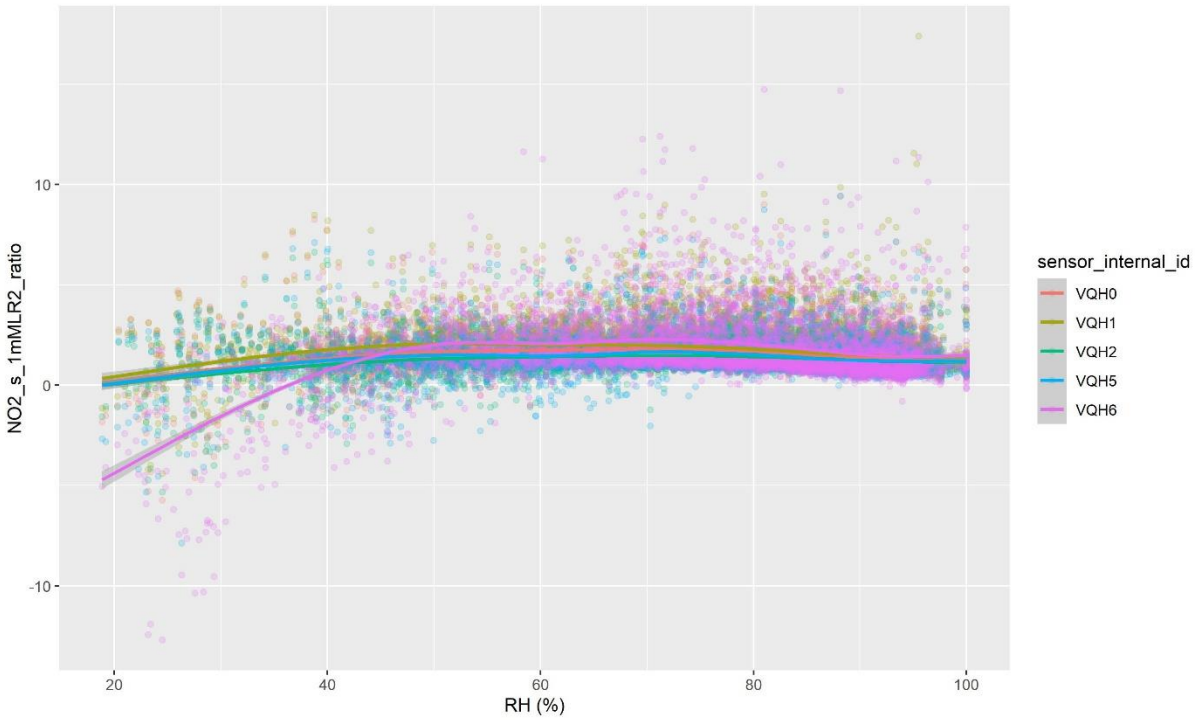


Figure 35: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with multiple linear regression versus reference values in relation to relative humidity (%)

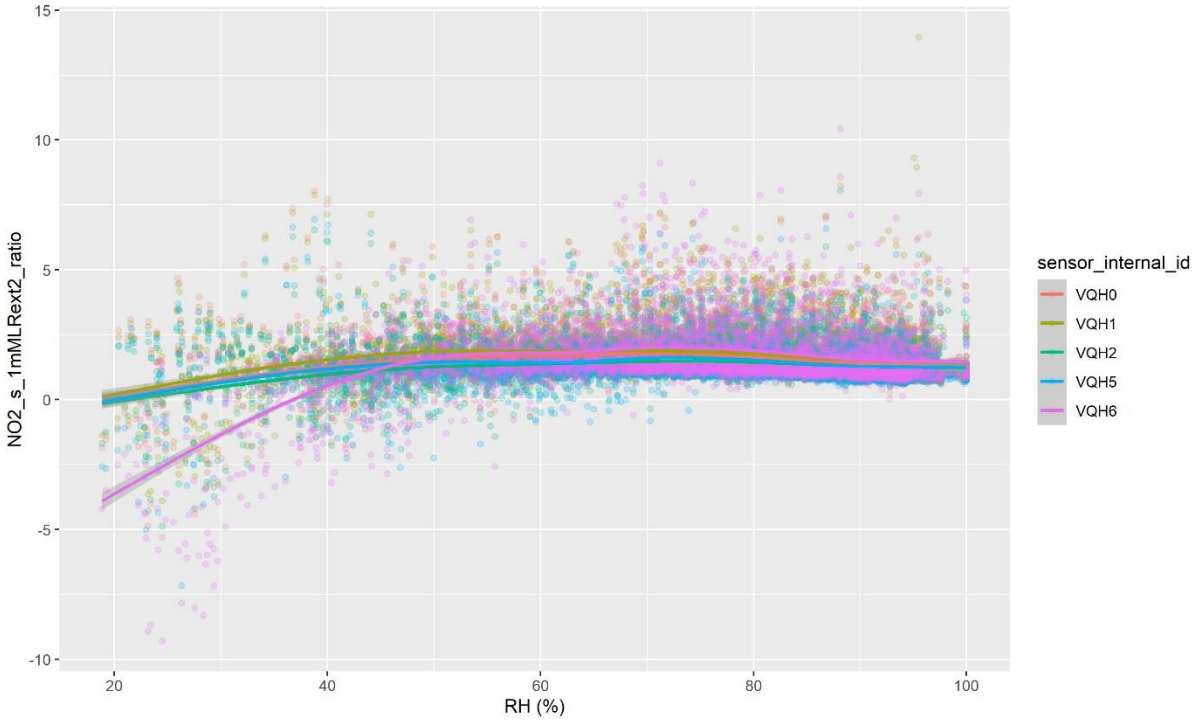


Figure 36: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to relative humidity (%)

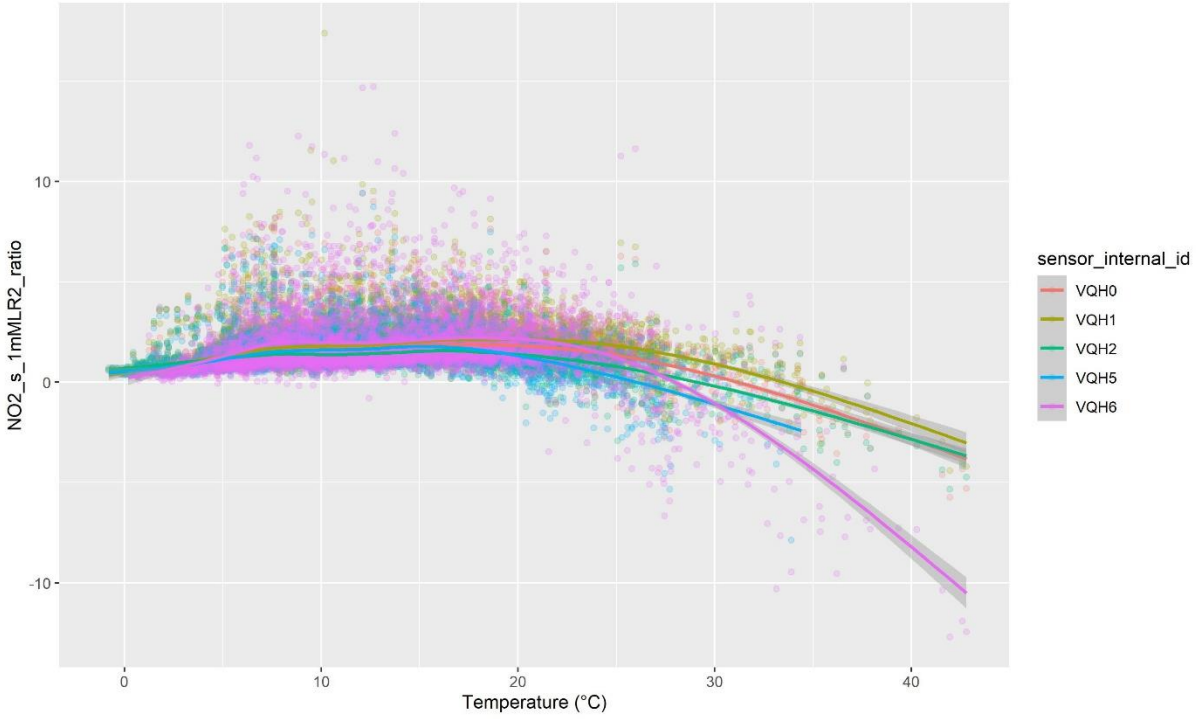


Figure 37: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with multiple linear regression versus reference values in relation to temperature (°C)

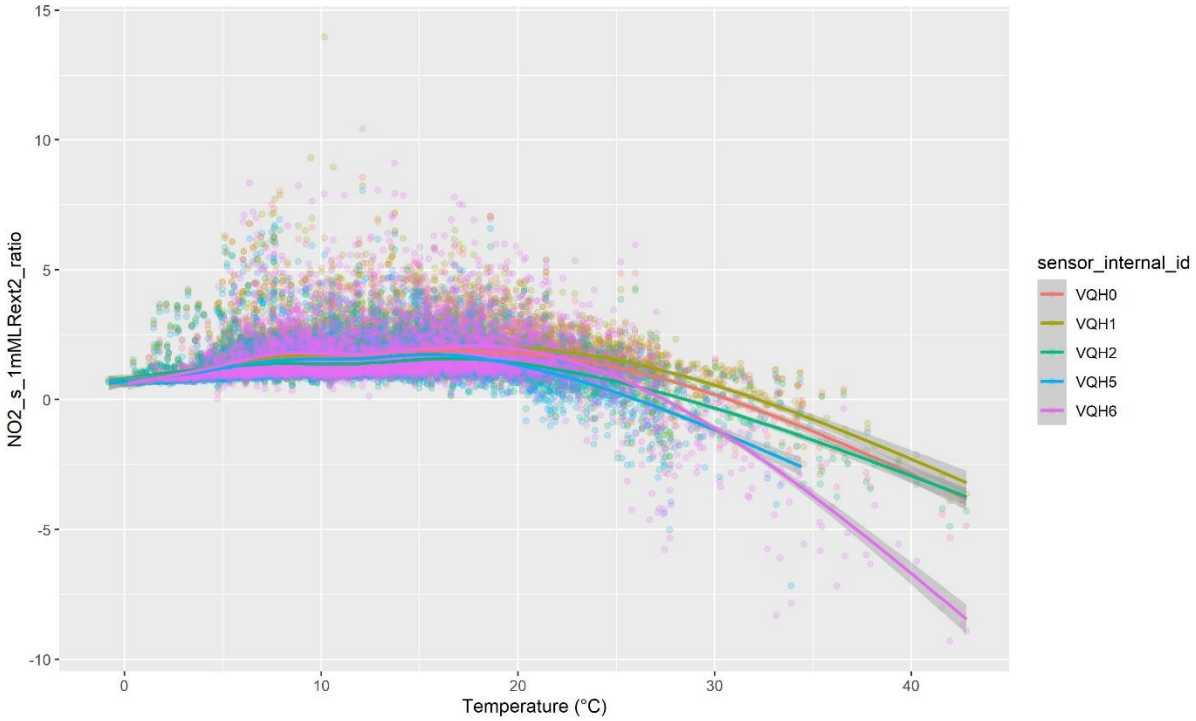


Figure 38: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to temperature (°C)

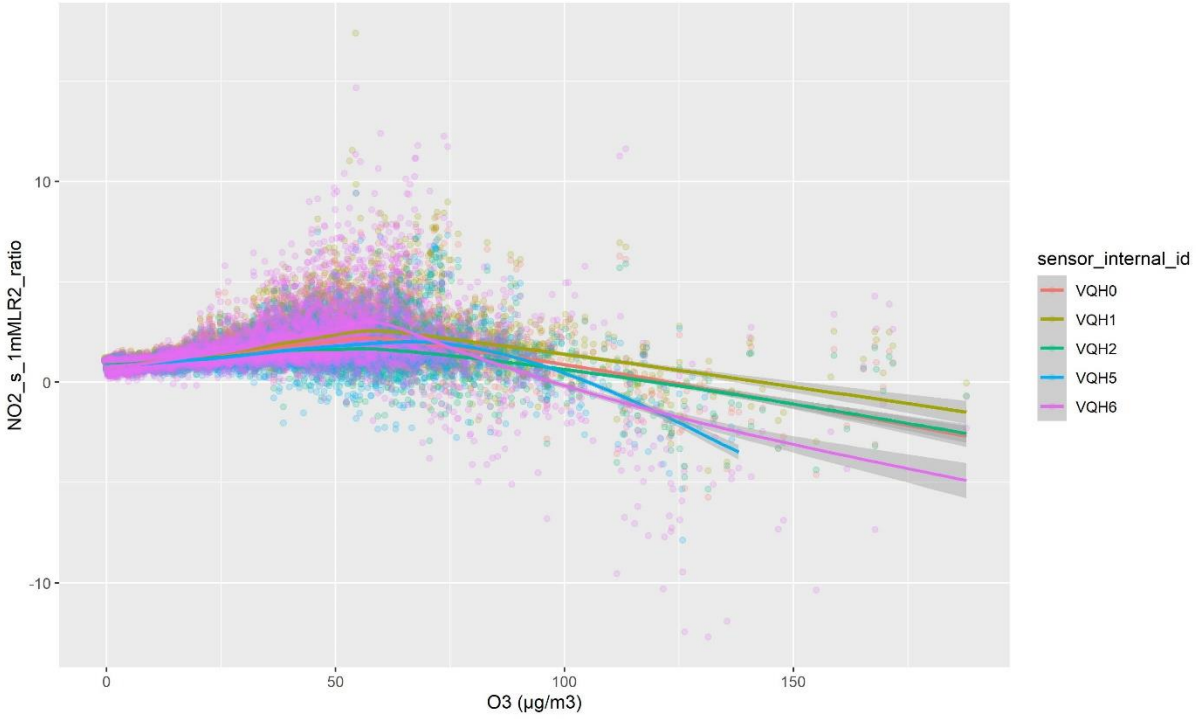


Figure 39: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with multiple linear regression versus reference values in relation to ozone (µg/m³)

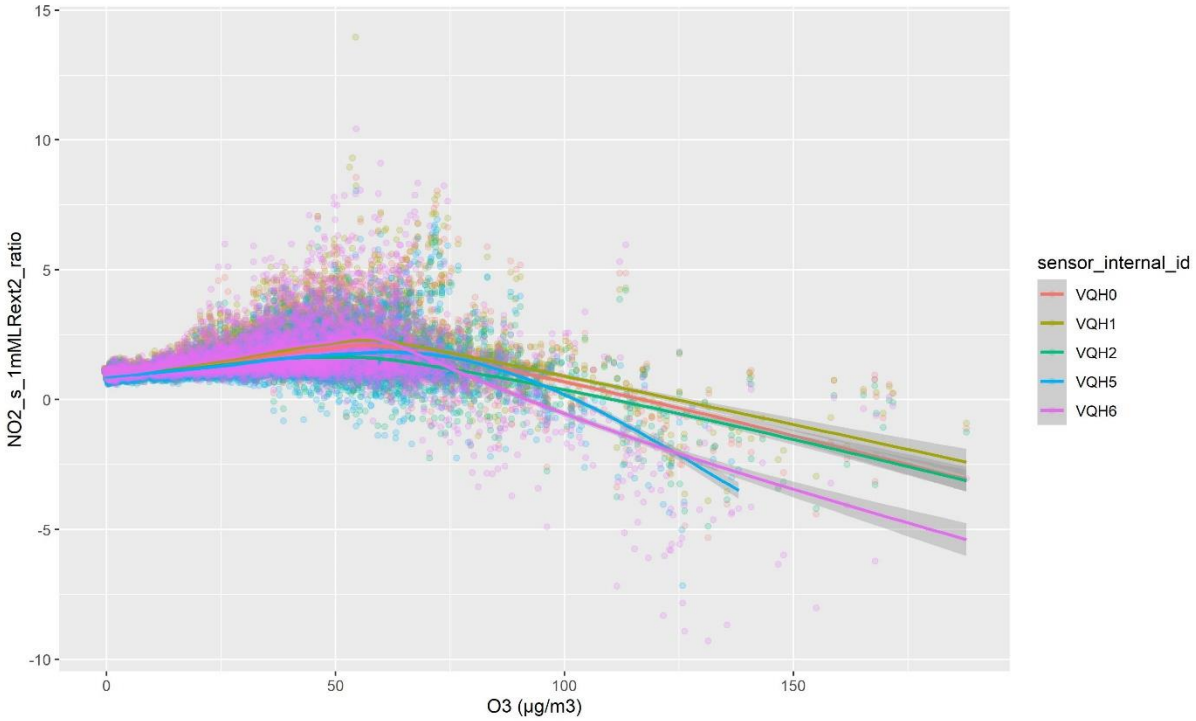


Figure 40: Alphasense B43F NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to ozone (µg/m³)

3.3.4 Descriptive parameters

Table 12: Alphasense B43F NO_2 sensor: Descriptive parameters for sensors calibrated with multiple linear regression and extended multiple linear regression. ID: sensor idea, n: number of values, R^2: coefficient of determination, U_{bs}: between sampler uncertainty

		Calibration		Evaluation				
	ID	n	R^2	n	mean bias (µg/m³)	R^2	u_{bs} (µg/m³)	u_{bs} (%)
NO_2_s_1mMLR2	VQH0	845	0.95	6849	7.84	0.48		
NO_2_s_1mMLR2	VQH1	846	0.92	7058	11.30	0.44		
NO_2_s_1mMLR2	VQH2	846	0.94	5855	4.36	0.59		
NO_2_s_1mMLR2	VQH5	846	0.91	5978	5.10	0.51		
NO_2_s_1mMLR2	VQH6	846	0.78	6425	11.70	0.19		
NO_2_s_1mMLR2	all sensors			32165			16.82	45.29
NO_2_s_1mMLRext2	VQH0	736	0.96	6408	7.73	0.54		
NO_2_s_1mMLRext2	VQH1	737	0.95	6611	10.37	0.59		
NO_2_s_1mMLRext2	VQH2	737	0.96	5432	4.58	0.64		
NO_2_s_1mMLRext2	VQH5	737	0.94	5556	5.33	0.63		
NO_2_s_1mMLRext2	VQH6	737	0.90	6008	9.72	0.36		
NO_2_s_1mMLRext2	all sensors			30015			14.99	41.24

3.3.5 Relative expanded uncertainty

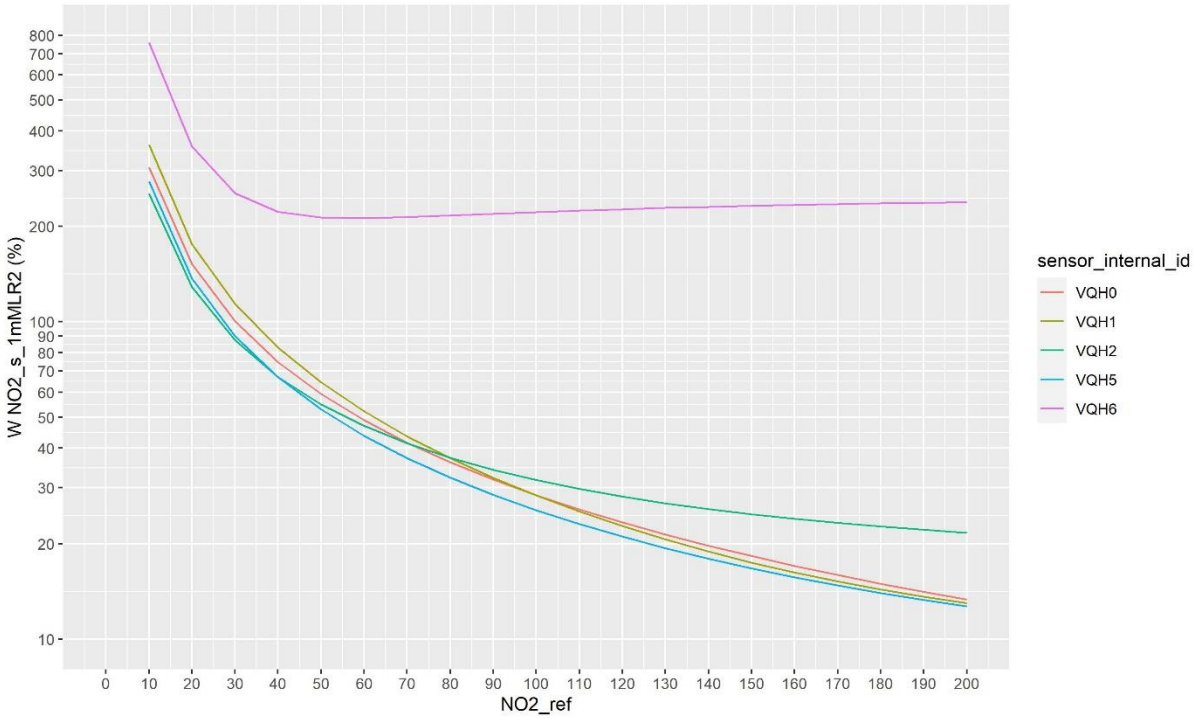


Figure 41: Alphasense B43F NO_2 sensor: Relative expanded uncertainty (W (%)) of sensor calibrated with multiple linear regression according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logarithmic scale

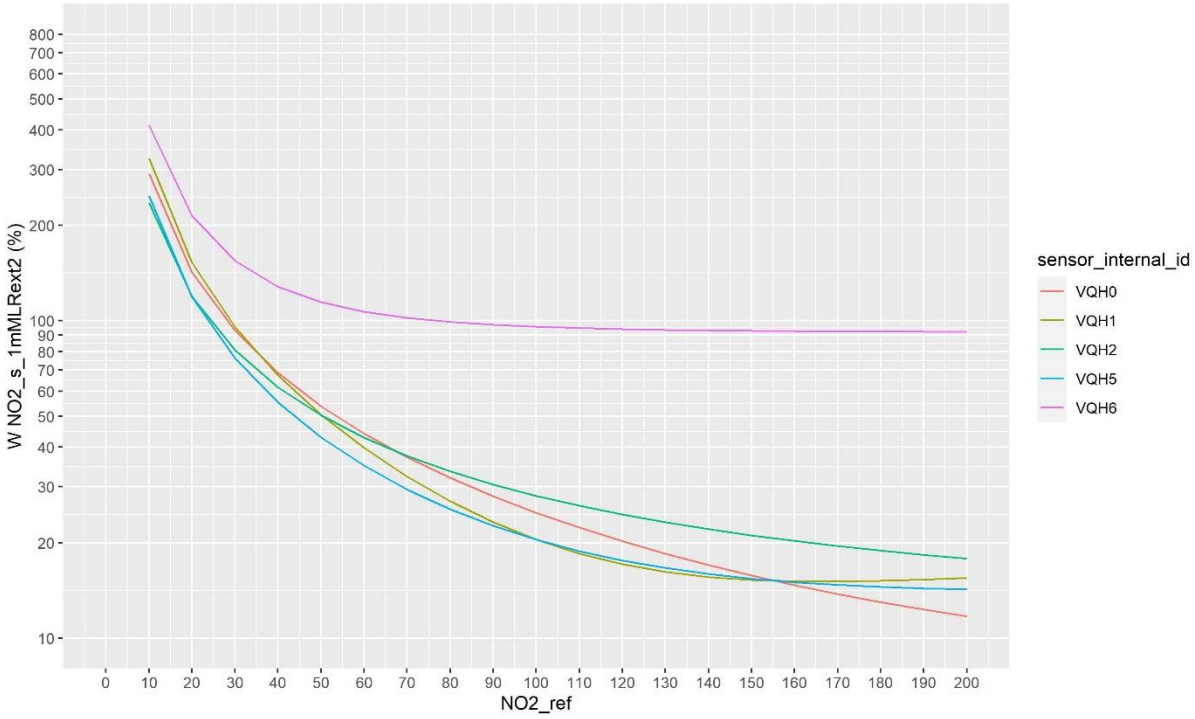


Figure 42: Alphasense B43F NO_2 sensor: Relative expanded uncertainty (W (%)) of sensor calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logarithmic scale

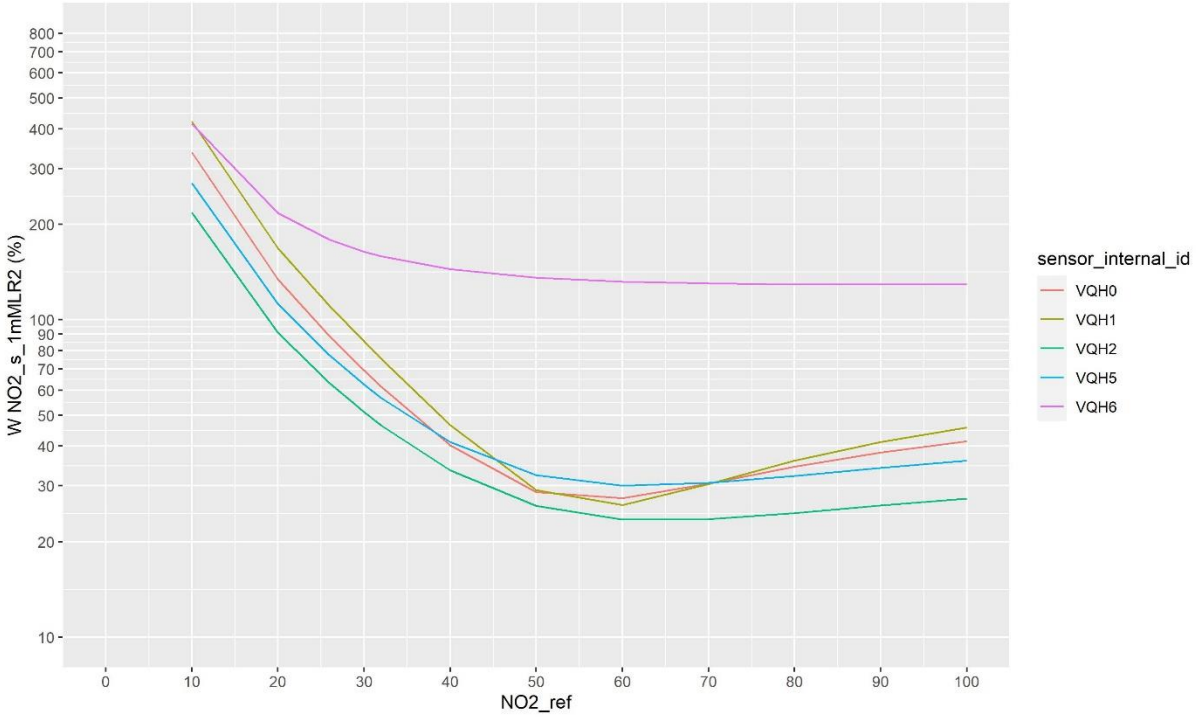


Figure 43: Alphasense B43F NO_2 sensor: Relative expanded uncertainty (W (%)) of sensors calibrated with multiple linear regression according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logaritmic scale.

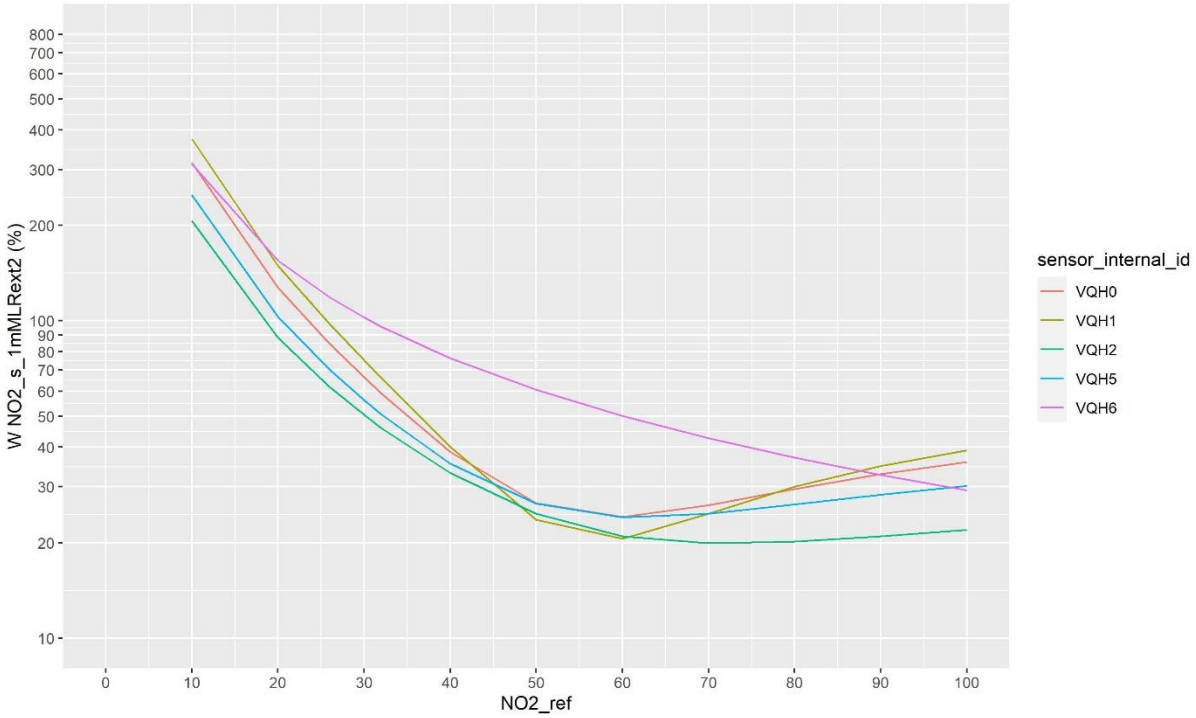


Figure 44: Alphasense B43F NO_2 sensor: Relative expanded uncertainty (W (%)) of sensors calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logaritmic scale.

Table 13: Alphasense B43F NO_2 sensor: Relative expanded uncertainty of sensors calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO_2 hourly reference concentrations of 100 µg/m³ (LAT), 140 µg/m³ (UAT) and 200 µg/m³ (LV)

	ID	NO_2 µg/m³	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLR2	VQH0	100	12.90	5.95	28.41
NO_2_s_1mMLR2	VQH1	100	12.89	5.90	28.35
NO_2_s_1mMLR2	VQH2	100	12.35	9.94	31.71
NO_2_s_1mMLR2	VQH5	100	12.54	2.25	25.48
NO_2_s_1mMLR2	VQH6	100	35.74	104.97	221.78
NO_2_s_1mMLRext2	VQH0	100	11.68	4.22	24.84
NO_2_s_1mMLRext2	VQH1	100	10.15	1.14	20.43
NO_2_s_1mMLRext2	VQH2	100	11.21	8.44	28.07
NO_2_s_1mMLRext2	VQH5	100	10.17	-1.01	20.43
NO_2_s_1mMLRext2	VQH6	100	20.68	43.22	95.84
NO_2_s_1mMLR2	VQH0	140	12.90	4.89	19.71
NO_2_s_1mMLR2	VQH1	140	12.89	2.88	18.87
NO_2_s_1mMLR2	VQH2	140	12.35	13.07	25.69
NO_2_s_1mMLR2	VQH5	140	12.54	0.62	17.94
NO_2_s_1mMLR2	VQH6	140	35.74	157.27	230.40
NO_2_s_1mMLRext2	VQH0	140	11.68	2.24	17.00
NO_2_s_1mMLRext2	VQH1	140	10.15	-3.99	15.58
NO_2_s_1mMLRext2	VQH2	140	11.21	10.60	22.04
NO_2_s_1mMLRext2	VQH5	140	10.17	-4.59	15.94
NO_2_s_1mMLRext2	VQH6	140	20.68	61.93	93.27
NO_2_s_1mMLR2	VQH0	200	12.90	3.29	13.31
NO_2_s_1mMLR2	VQH1	200	12.89	-1.66	13.00
NO_2_s_1mMLR2	VQH2	200	12.35	17.76	21.64
NO_2_s_1mMLR2	VQH5	200	12.54	-1.81	12.67
NO_2_s_1mMLR2	VQH6	200	35.74	235.71	238.41
NO_2_s_1mMLRext2	VQH0	200	11.68	-0.72	11.71
NO_2_s_1mMLRext2	VQH1	200	10.15	-11.69	15.49
NO_2_s_1mMLRext2	VQH2	200	11.21	13.84	17.81
NO_2_s_1mMLRext2	VQH5	200	10.17	-9.97	14.24
NO_2_s_1mMLRext2	VQH6	200	20.68	89.98	92.32

Table 14: Alphasense B43F NO_2 sensor: Relative expanded uncertainty of sensors calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO2 daily reference concentrations of 26 µg/m³ (LAT), 32 µg/m³ (UAT) and 40 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLR2	VQH0	26	7.15	9.07	88.83
NO_2_s_1mMLR2	VQH1	26	7.13	12.49	110.62
NO_2_s_1mMLR2	VQH2	26	6.46	5.06	63.14
NO_2_s_1mMLR2	VQH5	26	8.02	6.07	77.33
NO_2_s_1mMLR2	VQH6	26	20.75	10.49	178.83
NO_2_s_1mMLRext2	VQH0	26	6.63	8.80	84.77
NO_2_s_1mMLRext2	VQH1	26	5.67	11.37	97.72
NO_2_s_1mMLRext2	VQH2	26	6.14	5.22	61.96
NO_2_s_1mMLRext2	VQH5	26	6.63	6.28	70.26
NO_2_s_1mMLRext2	VQH6	26	11.59	10.17	118.63
NO_2_s_1mMLR2	VQH0	32	7.15	6.75	61.47
NO_2_s_1mMLR2	VQH1	32	7.13	9.71	75.31
NO_2_s_1mMLR2	VQH2	32	6.46	3.67	46.46
NO_2_s_1mMLR2	VQH5	32	8.02	4.27	56.77
NO_2_s_1mMLR2	VQH6	32	20.75	14.59	158.53
NO_2_s_1mMLRext2	VQH0	32	6.63	6.74	59.08
NO_2_s_1mMLRext2	VQH1	32	5.67	8.93	66.12
NO_2_s_1mMLRext2	VQH2	32	6.14	4.06	45.98
NO_2_s_1mMLRext2	VQH5	32	6.63	4.67	50.71
NO_2_s_1mMLRext2	VQH6	32	11.59	10.07	95.96
NO_2_s_1mMLR2	VQH0	40	7.15	3.67	40.19
NO_2_s_1mMLR2	VQH1	40	7.13	6.01	46.64
NO_2_s_1mMLR2	VQH2	40	6.46	1.82	33.58
NO_2_s_1mMLR2	VQH5	40	8.02	1.87	41.16
NO_2_s_1mMLR2	VQH6	40	20.75	20.06	144.31
NO_2_s_1mMLRext2	VQH0	40	10.87	6.63	38.67
NO_2_s_1mMLRext2	VQH1	40	13.80	5.67	40.14
NO_2_s_1mMLRext2	VQH2	40	6.38	6.14	33.15
NO_2_s_1mMLRext2	VQH5	40	7.89	6.63	35.50
NO_2_s_1mMLRext2	VQH6	40	10.28	11.59	76.32

Table 15: Alphasense B43F NO_2 sensor: Parameters of orthogonal regression of hourly and daily sensor data calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) versus reference NO_2

		hourly values		daily values	
	ID	slope	intercept (µg/m³)	slope	intercept (µg/m³)
NO2_s_1mMLR2	VQH0	0.97	8.61	0.61	19.09
NO2_s_1mMLR2	VQH1	0.92	13.45	0.54	24.51
NO2_s_1mMLR2	VQH2	1.08	2.11	0.77	11.07
NO2_s_1mMLR2	VQH5	0.96	6.30	0.70	13.85
NO2_s_1mMLR2	VQH6	2.31	-25.77	1.68	-7.29
NO2_s_1mMLRext2	VQH0	0.95	9.15	0.66	17.75
NO2_s_1mMLRext2	VQH1	0.87	13.98	0.59	21.93
NO2_s_1mMLRext2	VQH2	1.05	3.04	0.81	10.24
NO2_s_1mMLRext2	VQH5	0.91	7.95	0.73	13.25
NO2_s_1mMLRext2	VQH6	1.47	-3.53	0.98	10.62

3.3.6 Conclusions

Calibration with the parameters from the MLR regression functions leads to positive means in the sensor data in comparison with the reference data. When we look at the scatter plots of the ratio sensor data versus reference data in relation to temperature, relative humidity and O_3, we see that there is less scatter at lower relative humidity, higher temperature and higher O_3 concentrations in comparison with the uncalibrated sensor data (*NO2_s_2*), but negative values are still present.

The R^2 (between 0.19 and 0.59) for the sensor data calibrated with the parameters from MLR without O_3 (*NO2_s_1mMLR2*) are comparable to the uncalibrated sensor data, but the between sensor uncertainty (45 %) and the expanded relative uncertainty are smaller than for the uncalibrated sensor data (except for sensor VQH6).

The sensor data calibrated with the parameters from MLR with O_3 (*NO2_s_1mMLRext2*) show better performance characteristics than the MLR model without O_3 and in comparison with the uncalibrated sensor data. The R^2 varies between 0.54 and 0.64 for the sensors VQH0, VQH1, VQH2 an VQH5 and is 0.36 for VQH6. The mean biases vary between 5 and 10 µg/m^3. The between sensor uncertainty is 41 %. The relative expanded uncertainties are smaller.

The expanded uncertainty of the hourly sensor data *NO2_s_1mMLR2* and *NO2_s_1mMLRext2* at the LV (200 µg/m^3), the UAT (140 µg/m^3) and the LAT (100 µg/m^3) is ≤ 75 % for all sensors, except sensor VQH6. Except for this sensor VQH6, the expanded uncertainty is also ≤ 25 % at the LV for all sensors. At lower concentrations the expanded uncertainties increase. At the UAT also for four of the five sensors the data *NO2_s_1mMLRext2* have expanded uncertainties ≤ 25 %, at the LAT the expanded uncertainties are only ≤ 25 % for three sensors. For three of five sensors the calibrated values *NO2_s_1mMLR* have expanded uncertainties ≤ 25 % at the UAT, but at the LAT the expanded uncertainties are > than 25 % for all sensors .

The expanded uncertainty of the daily sensor data *NO2_s_1mMLR2* and *NO2_s_1mMLRext2* at the LV (40 µg/m), the UAT (32 µg/m^3) and the LAT (26 µg/m^3) is > 25 % for all sensors. Except for sensor VQH6, the expanded uncertainty for the sensor data *NO2_s_1mMLR* and *NO2_s_1mMLRext2* is ≤ 75 % at the LV and at the UAT. At the LAT the expanded uncertainty for the sensor data *NO2_s_1mMLRext2* is ≤ 75 % for two of the five sensors and for the sensor data *NO2_s_1mMLR2* for one of the five sensors.

Field Evaluation
Citytech 3E50 NO_2 sensor

Manufacturer: Citytech

Link to website manufacturer

Link to test protocol

4 Citytech 3E50 NO_2 sensor

4.1 Validation and data coverage

VQI1 gave a constant, very high value for the entire measurement period. This sensor is therefore not included in the analysis of the field data. Also VQI4 gave very high, although not constant, values for the entire period. This sensor is therefore also not included in the analysis. The data of VQI2 were marked as suspicious from January 28, 2020 on. From this moment on the sensor gave a very high constant value and later on unstable measurements. VQI3 stopped measuring on December 26, 2019. VQI5 became unstable after February 10, 2020. The data after this date were marked as suspicious.

Both negative and positive peaks occur in the raw sensor data. When these peaks occurred after a restart of the measurements, they were marked as invalid. Other peaks were marked as suspicious when they were remarkable higher of lower than the values of the other sensors.

During the field campaign the Citytech 3E50 sensors were not oriented according to the supplied manual. They were oriented with the membrane sideways instead of downwards. It is unknown to what extend this orientation affected the data.

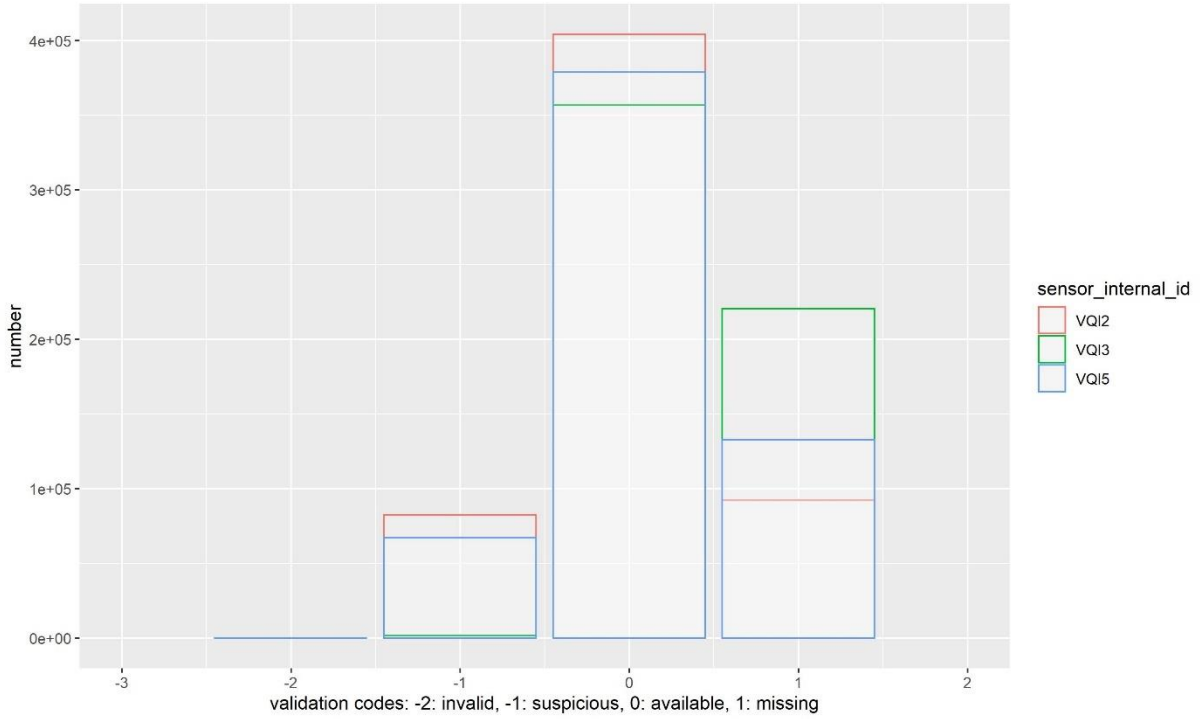


Figure 45: Citytech 3E50 NO_2 sensor: Number sensor minute values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 16: Citytech 3E50 NO_2 sensor: Number sensor minute values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQI2	2	82462	404200	92216	70
VQI3	2	1723	356924	220231	62
VQI5	113	67032	378875	132860	65

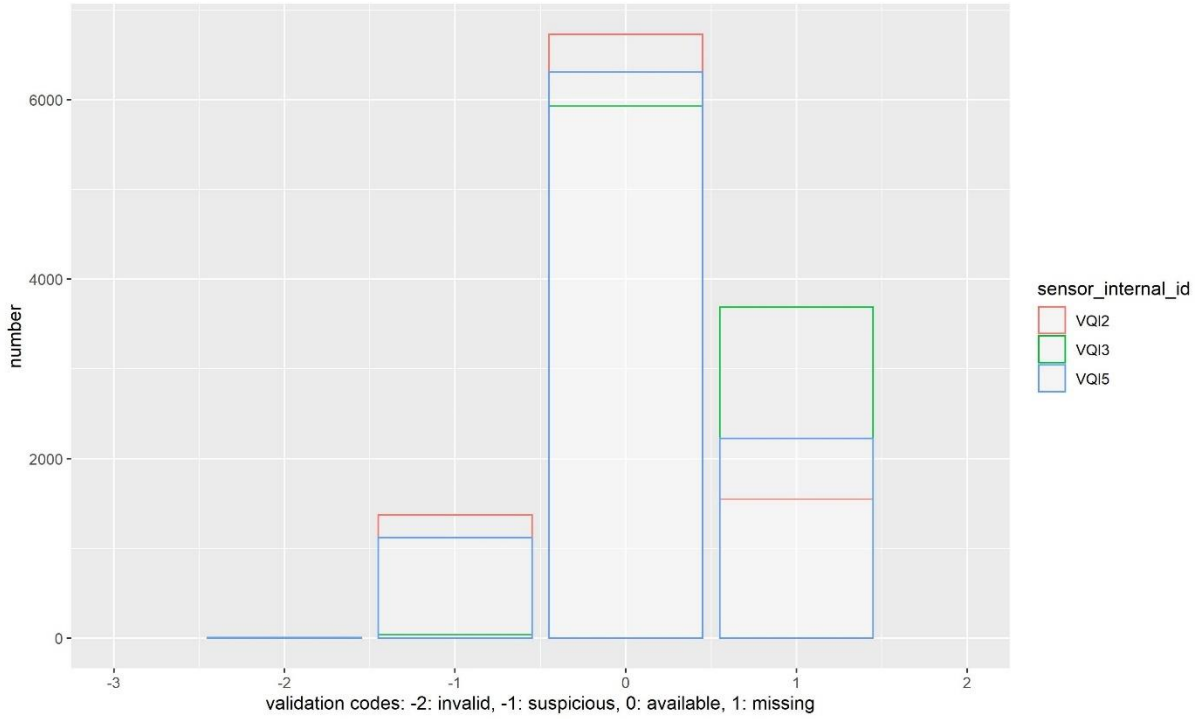


Figure 46: Citytech 3E50 NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 17: Citytech 3E50 NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQI2	0	1374	6728	1546	70
VQI3	0	38	5925	3685	61
VQI5	3	1120	6304	2221	65

4.2 Uncalibrated sensor data and sensor data calibrated with parameters from linear regression

4.2.1 Calibration parameters

As can be seen in the table with the descriptive parameters, there is almost no correlation (R^2 <= 0.05) between the uncalibrated sensor data and the reference data. Due to the low correlation, the parameters of the linear regression are not well defined. Therefore, the parameters of LR are not calculated nor used for this sensor type.

4.2.2 Comparison sensor versus reference

4.2.2.1 Time plot and scatter plots of hourly values

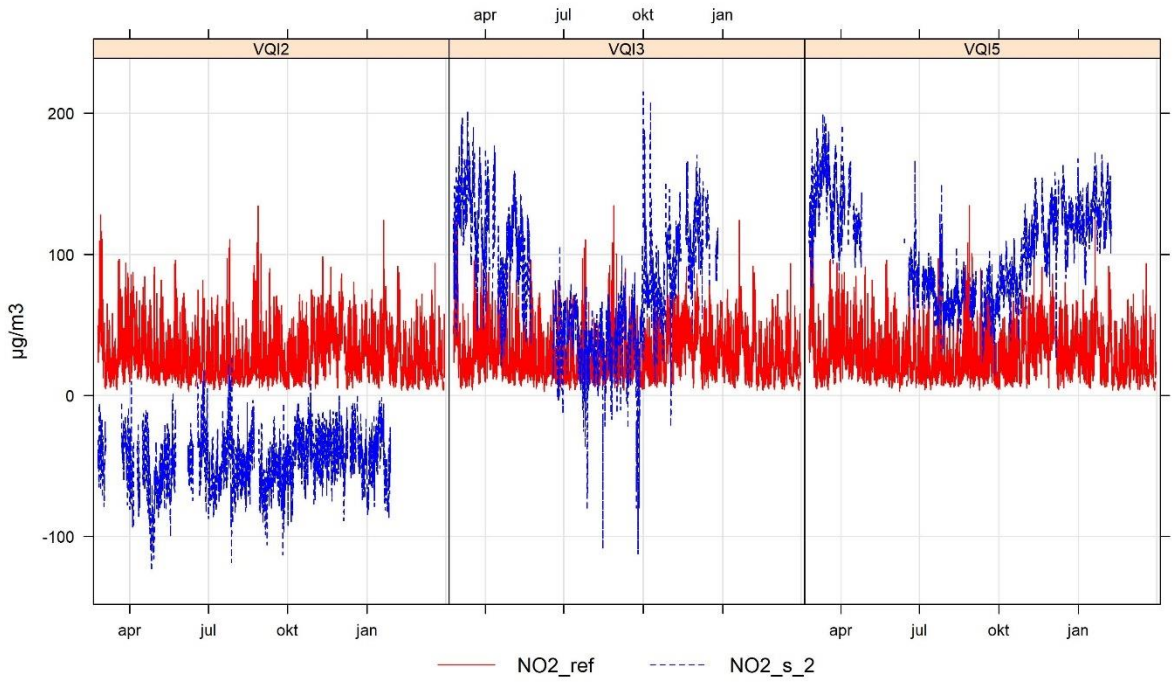


Figure 47: Citytech 3E50 NO_2 sensor: Time plot uncalibrated sensor hourly values and reference values (µg/m³)

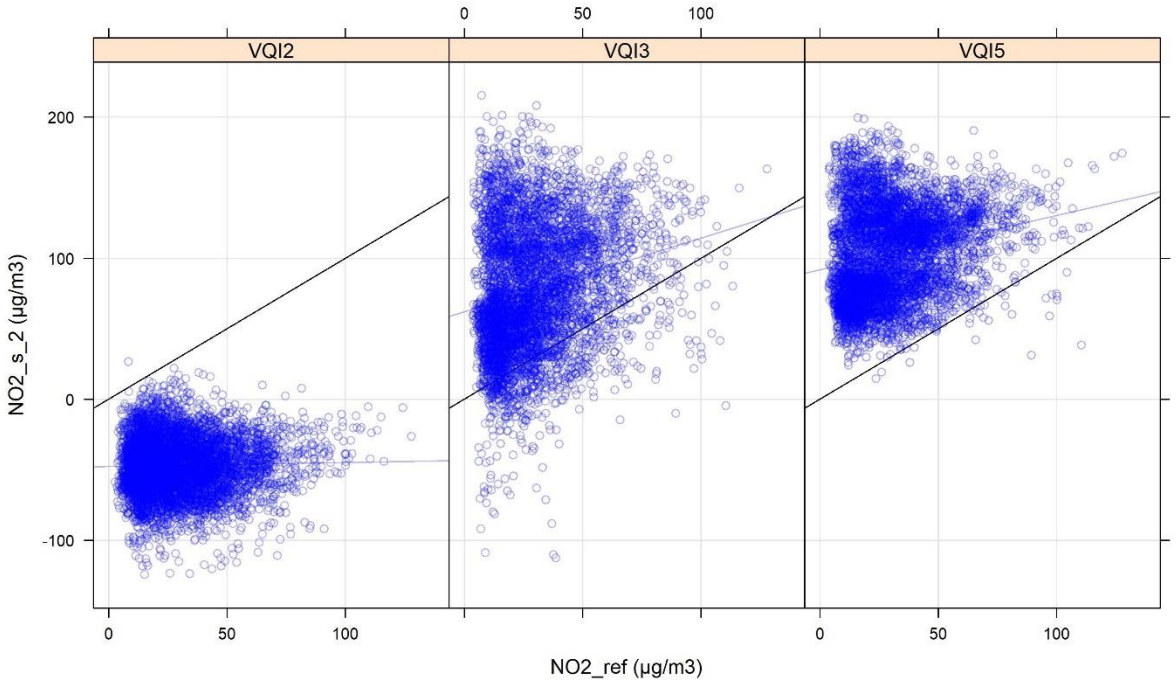


Figure 48: Citytech 3E50 NO_2 sensor: Scatter plot of uncalibrated sensor hourly values versus reference values (µg/m³)

4.2.2.2 Ratio of hourly sensor values versus reference values

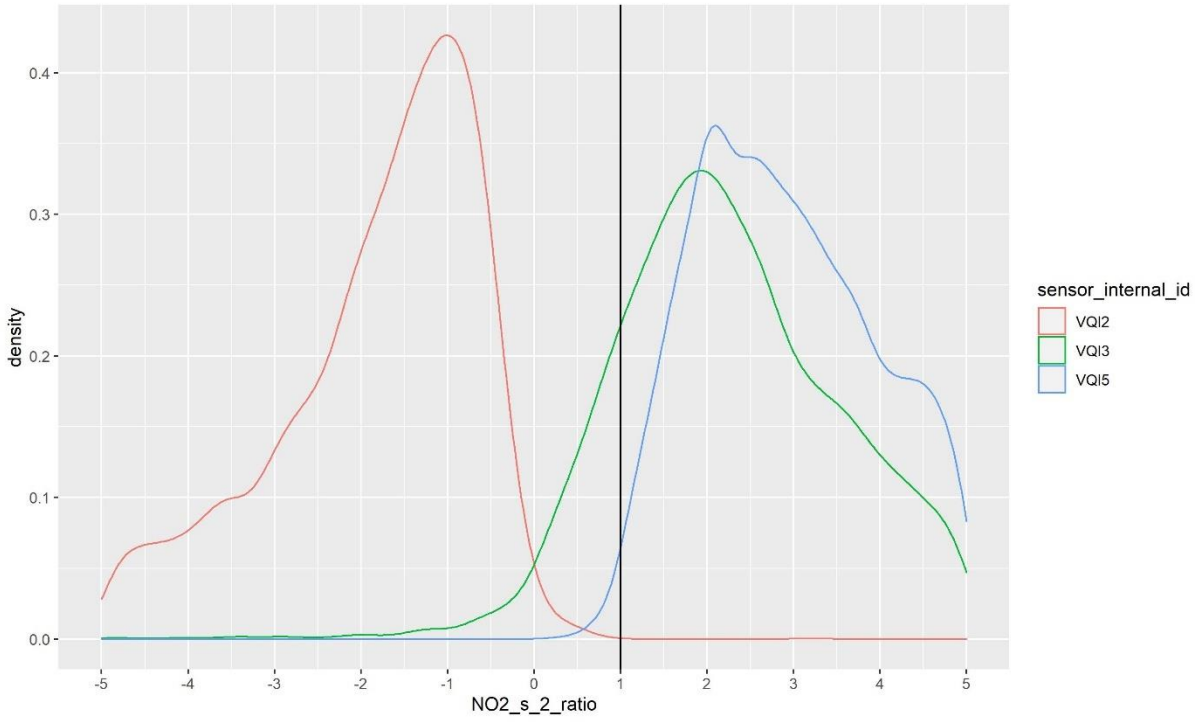


Figure 49: Citytech 3E50 NO_2 sensor: Density plot of uncalibrated ratio sensor hourly values versus reference values

4.2.3 Influence of time, temperature, relative humidity and O_3

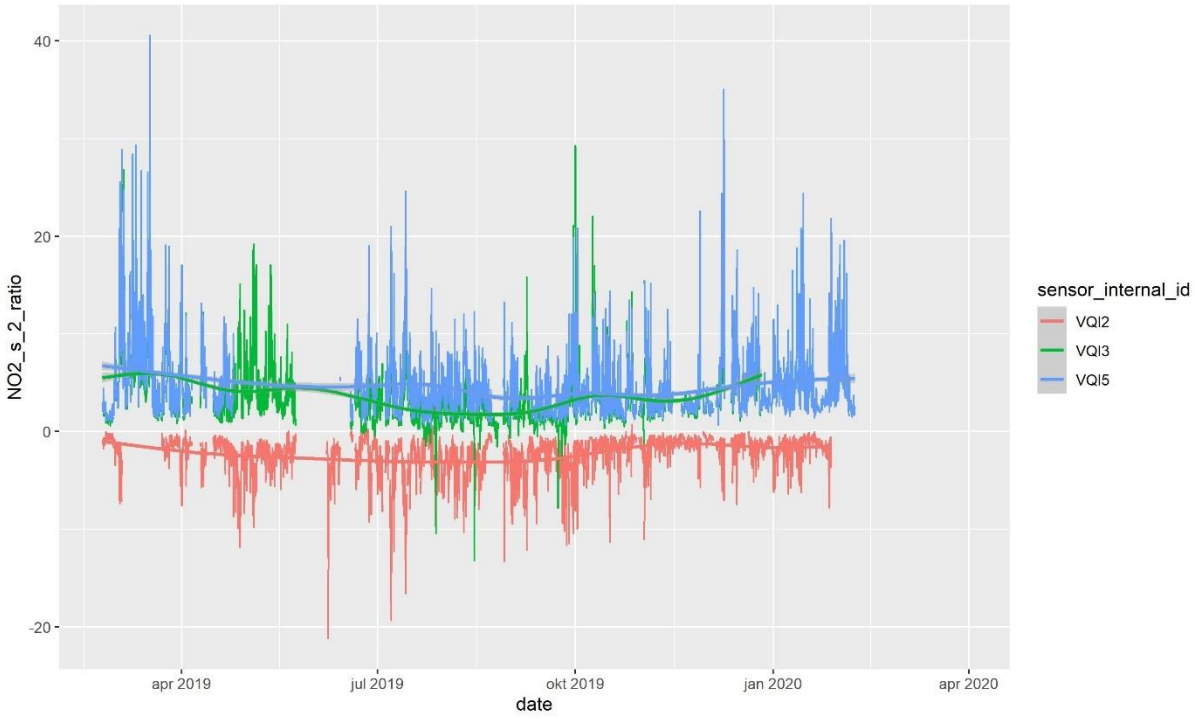


Figure 50: Citytech 3E50 NO_2 sensor: Time plot ratio sensor hourly values versus reference values (µg/m³)

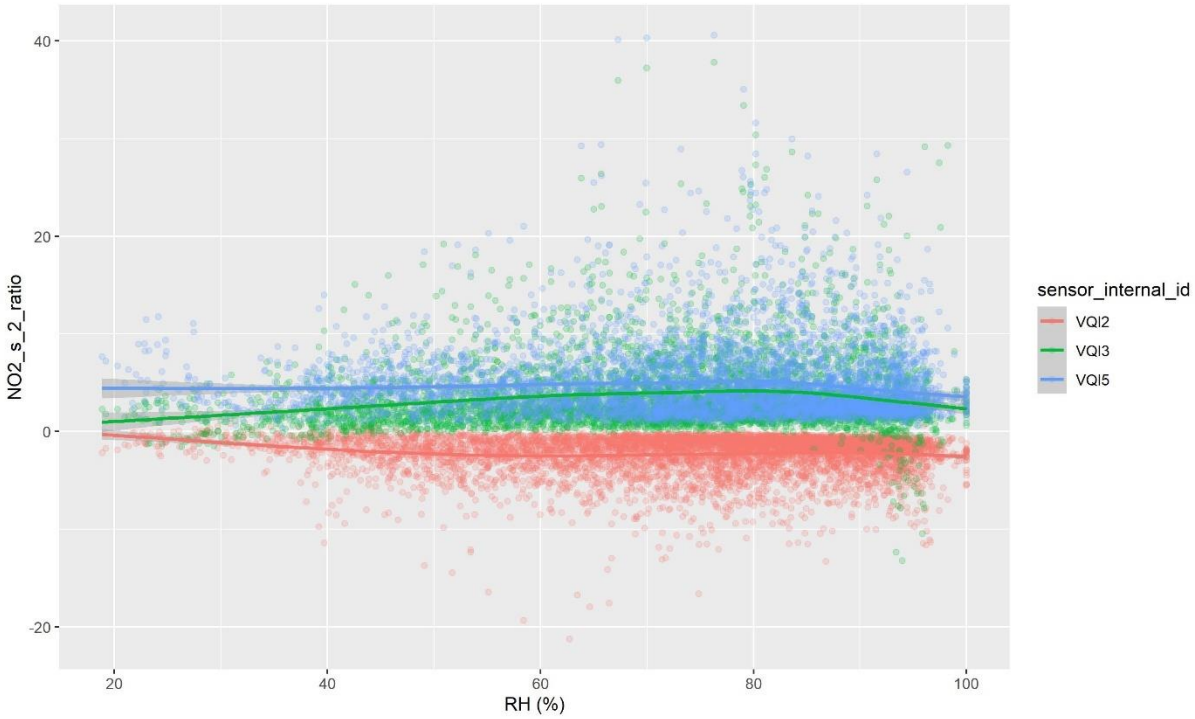


Figure 51: Citytech 3E50 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to relative humidity (%)

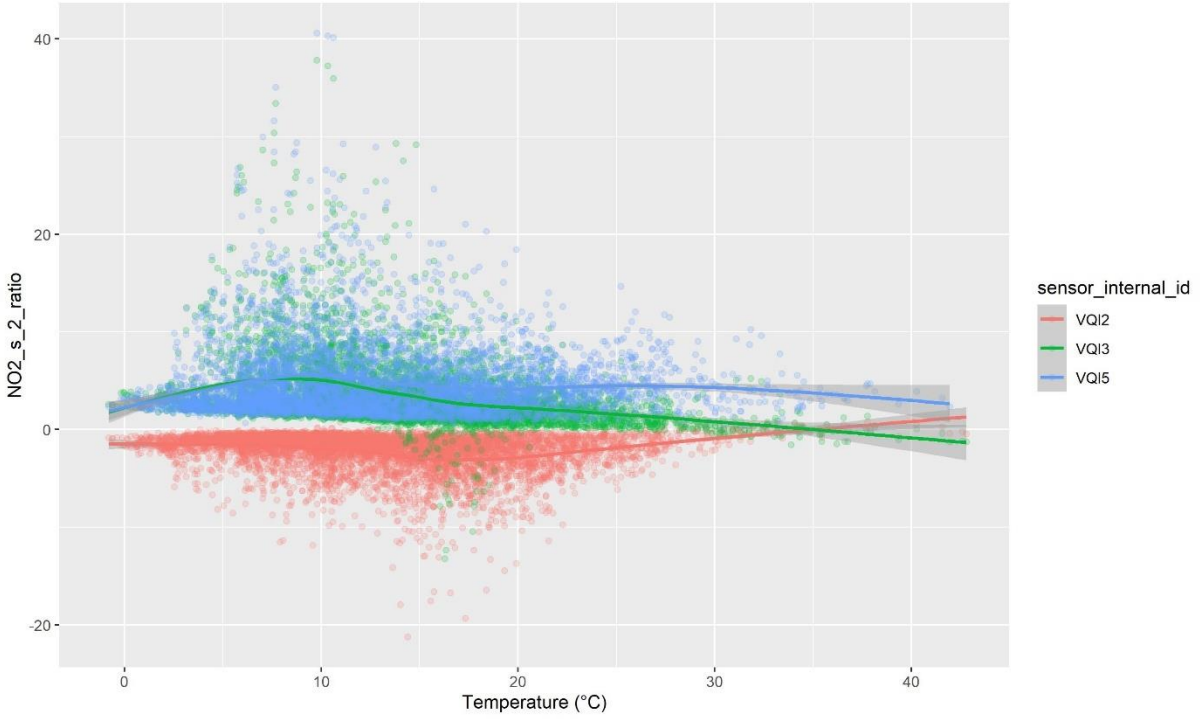


Figure 52: Citytech 3E50 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to temperature (°C)

Figure 53: Citytech 3E50 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to O_3 (µg/m³)

4.2.4 Descriptive parameters

Table 18: Citytech 3E50 NO_2 sensor: Descriptive parameters for uncalibrated sensors. ID: sensor idea, n: number of values, R^2: coefficient of determination, Ubs: between sampler uncertainty

		Evaluation				
	ID	n	mean bias (µg/m³)	R^2	u_{bs} (µg/m³)	u_{bs} (%)
NO_2_s_2	VQI2	6348	-77.27	0.00		
NO_2_s_2	VQI3	5581	47.76	0.05		
NO_2_s_2	VQI5	5943	72.73	0.05		
NO_2_s_2	all sensors	17872			66.00	156.43

4.2.5 Relative expanded uncertainty

The calculation of the relative expanded uncertainty according to the Guidance of of Equivalence is based on the linear regression of the sensor data versus the reference data. As there is almost no correlation between the sensor data and the reference data, this calculation is not executed.

4.2.6 Conclusions

There is no or only very little correlation (R^2 <= 0.05) between the uncalibrated sensor data (NO_2_s_2) and the reference data. The mean biases (between -77 and 72 µg/m³) of the sensor data in comparison to the reference data are large and very different for the individual sensors.

As there is no or very little correlation between the sensor data and the reference data, a calibration with linear regression parameters based on the first month of field data is not executed.

4.3 Sensor data calibrated with parameters from multiple linear regression

4.3.1 Calibration parameters

Table 19: Citytech 3E50 NO_2 sensor: Parameters from multiple linear regression (including NO_2 reference measurements (NO2_ref), temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	T	RH
VQI2	-31.6	-0.06	1.50	-0.33
VQI3	260.4	-0.47	-8.29	-0.48
VQI5	240.5	-0.51	-5.42	-0.39

Table 20: Citytech 3E50 NO_2 sensor: Parameters from extended multiple linear regression (including NO_2 reference measurements (NO2_ref), ozone reference measurements (O3_ref) temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	O_3_ref	T	RH
VQI2	-86.1	0.39	0.51	1.62	-0.07*
VQI3	122.6	0.59	1.12	-7.49	0.20
VQI5	77.8	0.74	1.34	-4.51	0.40

Variable not significant at 0.05 significance level

As can be seen in the table with the descriptive parameters, adding O_3 to the MRL significantly improves the calibrated sensor data. In fact, there is almost no correlation ($R^2 \leq 0.07$) between the reference data and the sensor data calibrated with the MLR parameters without O_3 and therefore we will not discuss these calibrated sensor data *NO2_s_1mMLR2* any further.

4.3.2 Comparison sensor versus reference

4.3.2.1 Time plot and scatter plots of hourly values

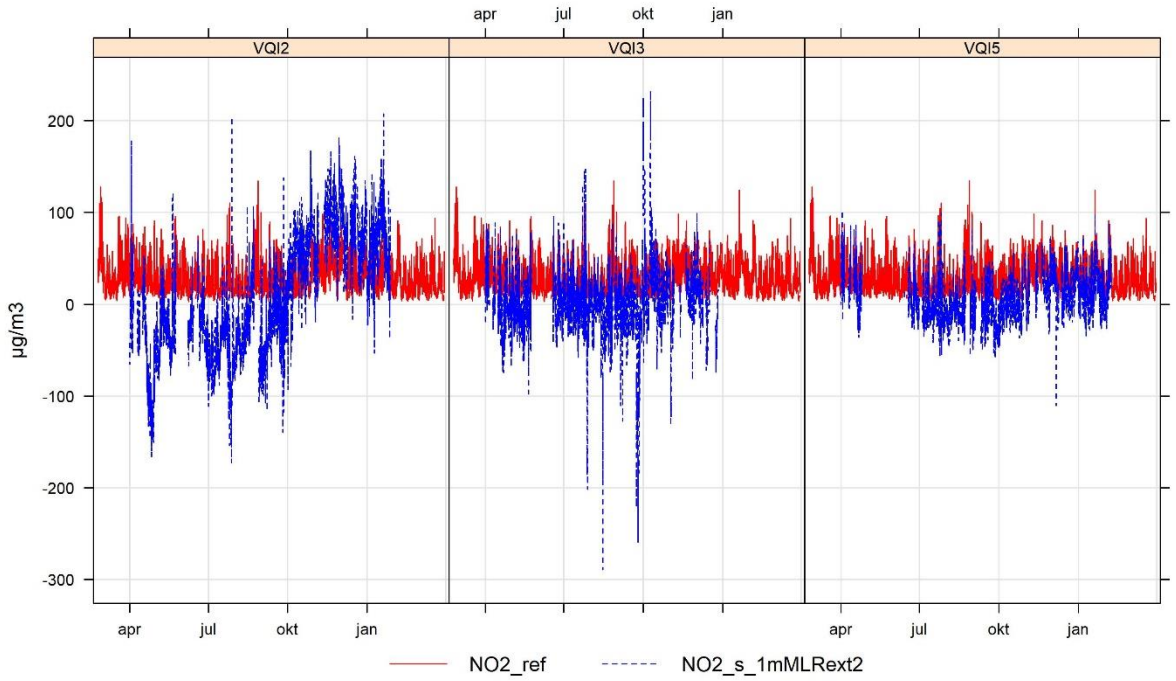


Figure 54: Citytech 3E50 NO_2 sensor: Time plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

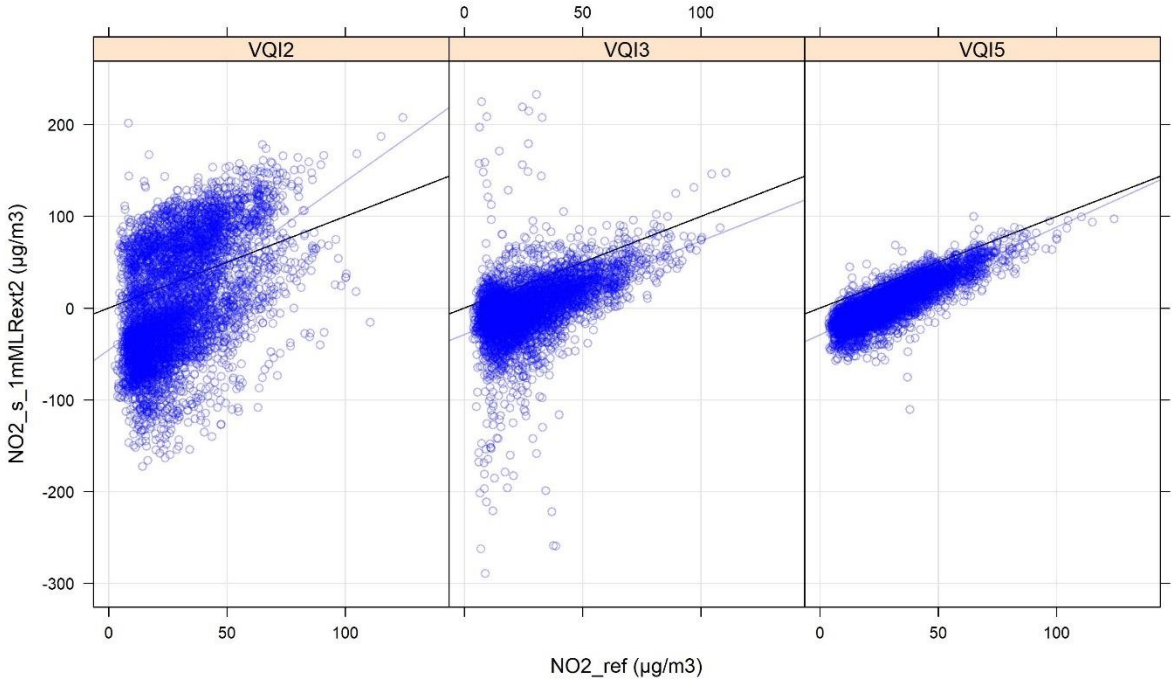


Figure 55: Citytech 3E50 NO_2 sensor: Scatter plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

4.3.2.2 Ratio of hourly sensor values versus reference values

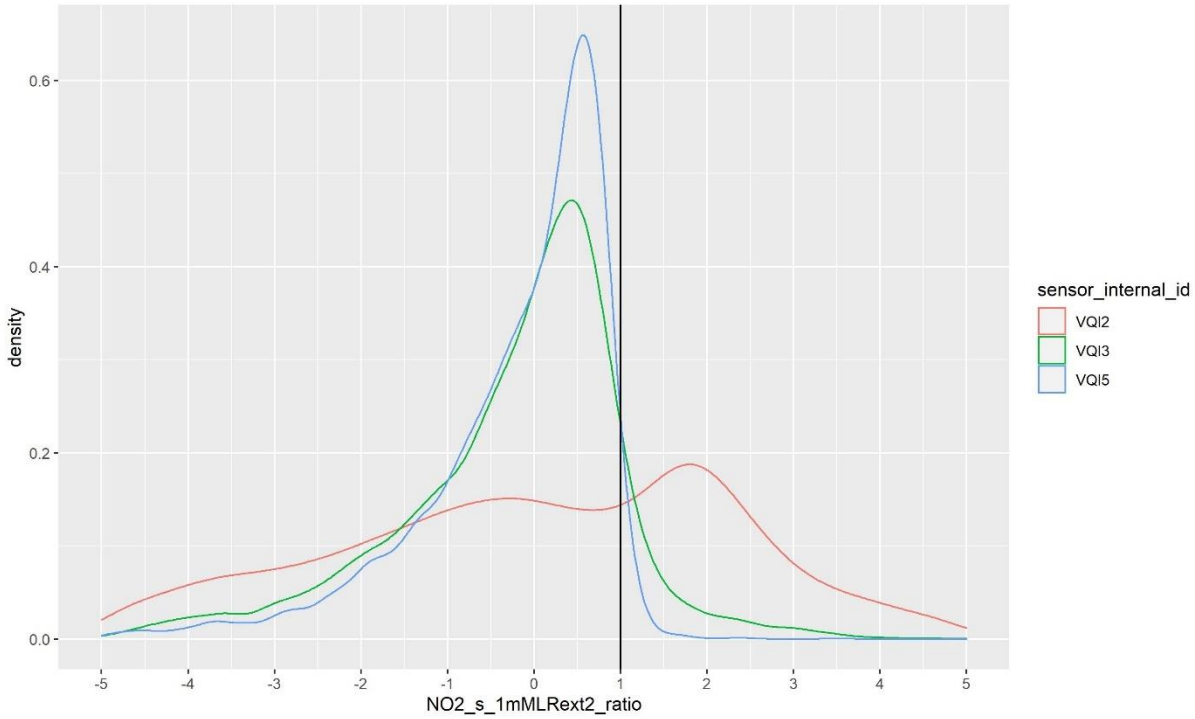


Figure 56: Citytech 3E50 NO_2 sensor: Density plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values

4.3.3 Influence of time, temperature, relative humidity and O_3

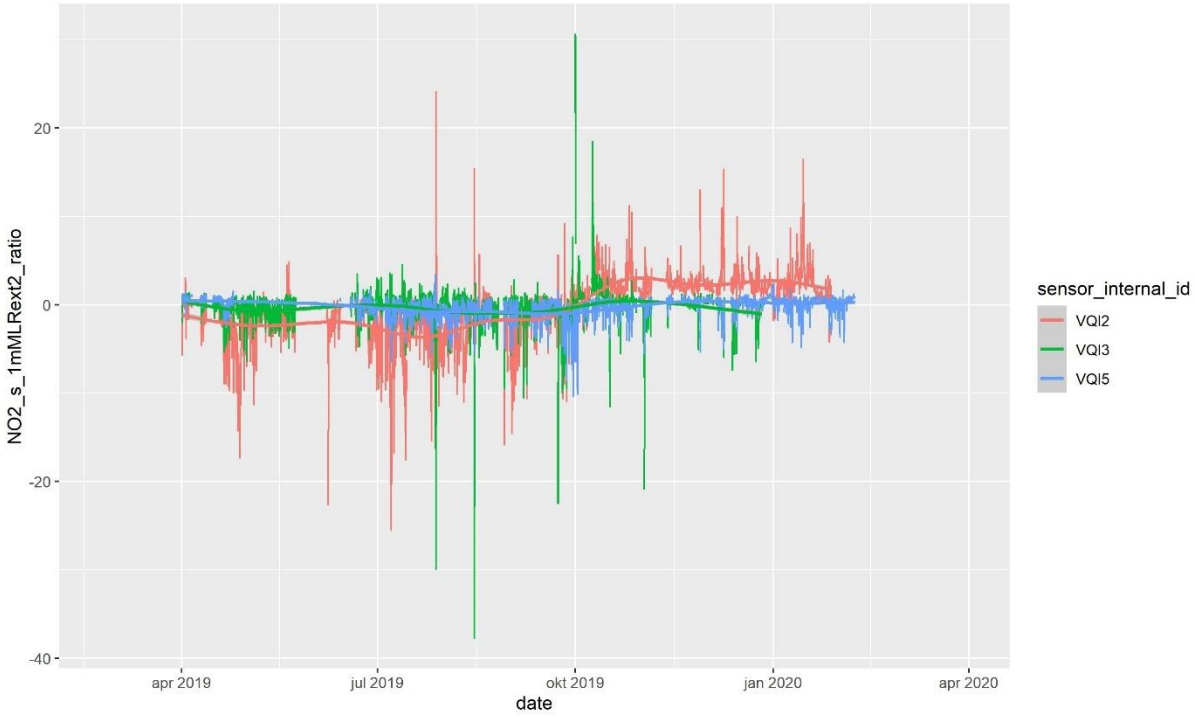


Figure 57: Citytech 3E50 NO_2 sensor: Time plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values (µg/m³)

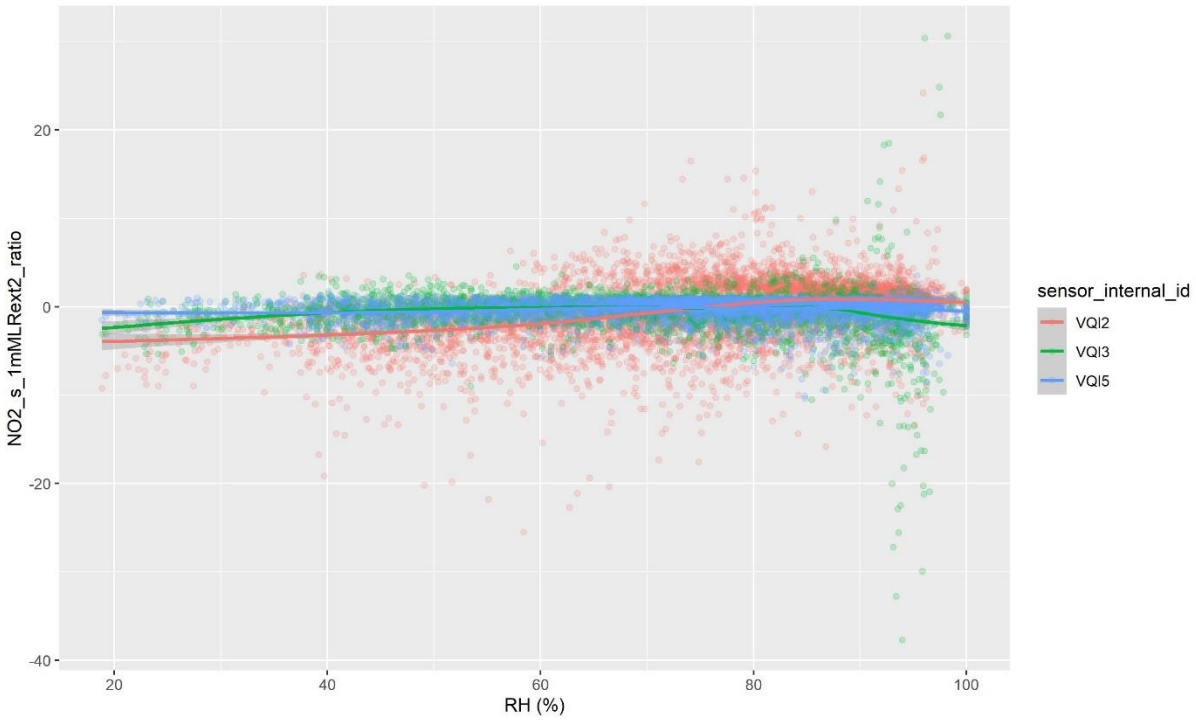


Figure 58: Citytech 3E50 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to relative humidity (%)

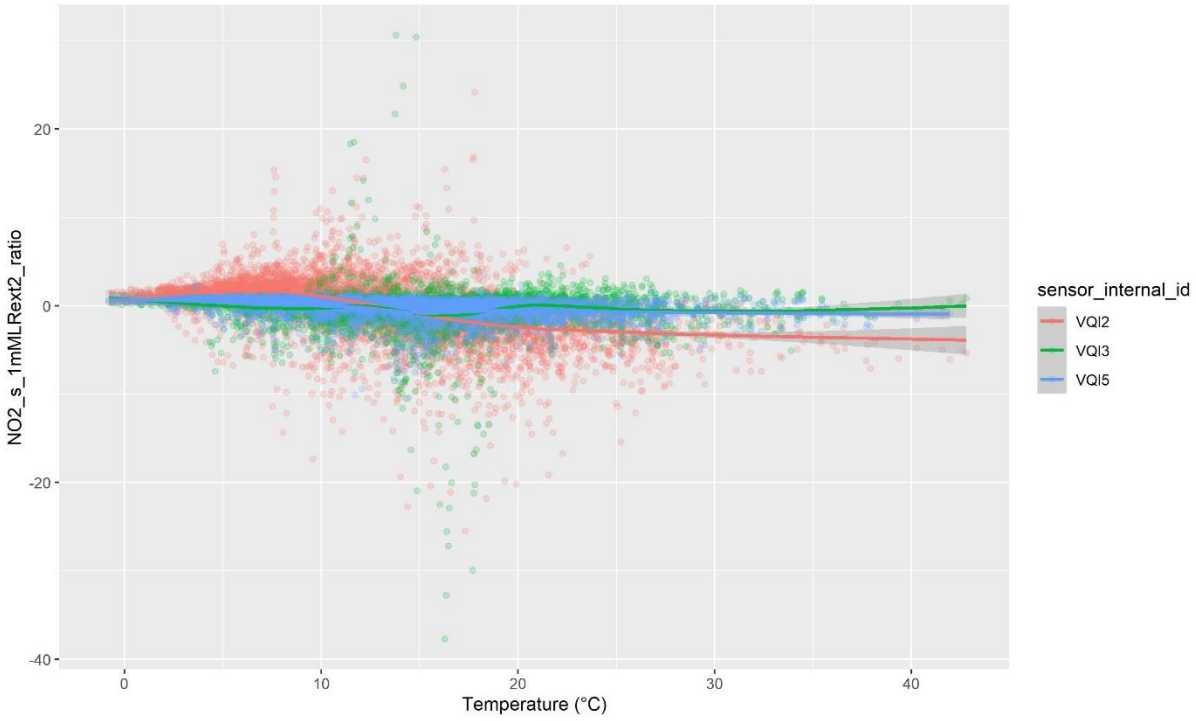


Figure 59: Citytech 3E50 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to temperature (°C)

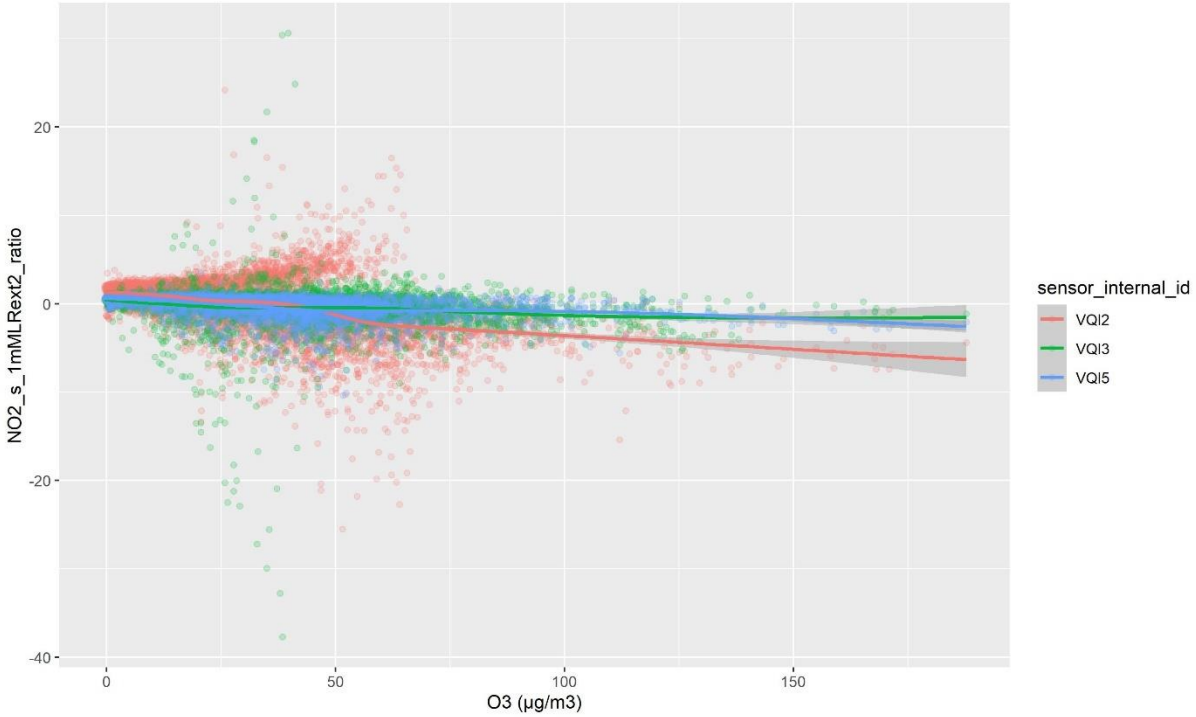


Figure 60: Citytech 3E50 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to ozone (µg/m³)

4.3.4 Descriptive parameters

Table 21: Citytech 3E50 NO_2 sensor: Descriptive parameters for sensors calibrated with multiple linear regression and extended multiple linear regression. ID: sensor idea, n: number of values, R^2: coefficient of determination, Ubs: between sampler uncertainty

		Calibration		Evaluation				
	ID	n	R^2	n	mean bias (µg/m³)	R^2	u_{bs} (µg/m³)	u_{bs} (%)
NO_2_s_1mMLR2	VQI2	426	0.02	5877	172.56	0.07		
NO_2_s_1mMLR2	VQI3	846	0.33	4699	42.12	0.04		
NO_2_s_1mMLR2	VQI5	845	0.36	5050	50.72	0.03		
NO_2_s_1mMLR2	all sensors			15626			191.79	155.87
NO_2_s_1mMLRext2	VQI2	417	0.55	5605	-21.19	0.24		
NO_2_s_1mMLRext2	VQI3	737	0.62	4457	-28.36	0.24		
NO_2_s_1mMLRext2	VQI5	736	0.82	4795	-23.97	0.70		
NO_2_s_1mMLRext2	all sensors			14857			33.74	652.60

4.3.5 Relative expanded uncertainty

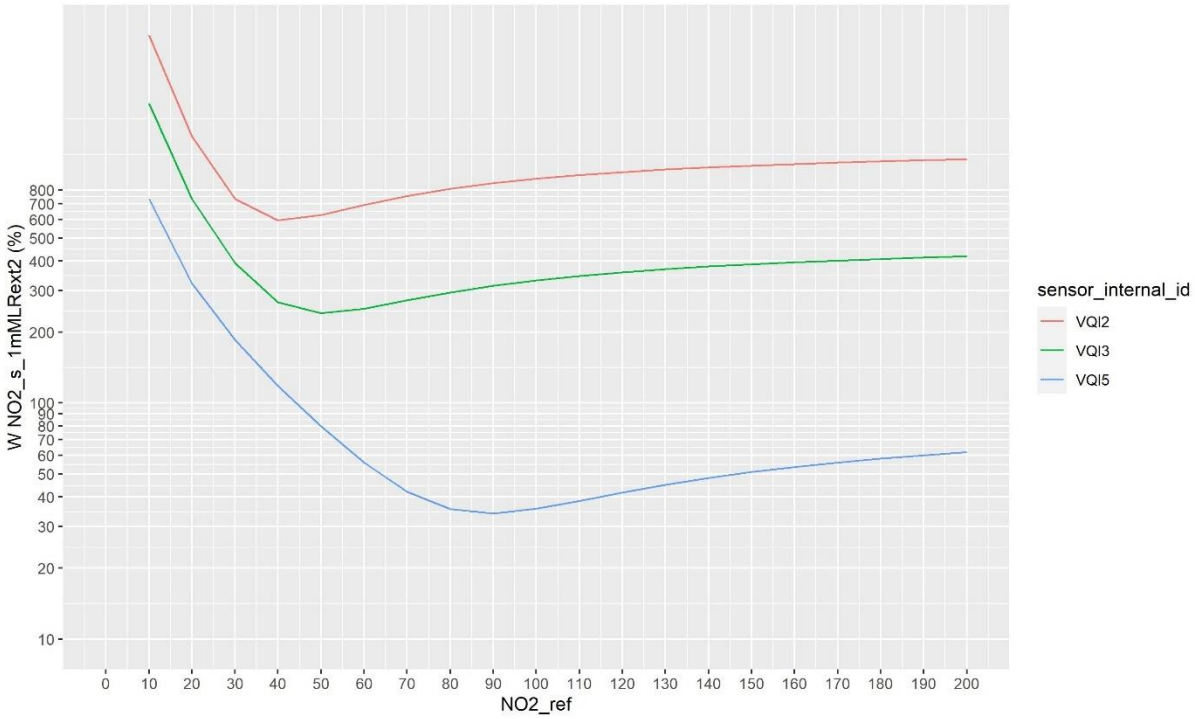


Figure 61: Citytech 3E50 NO_2 sensor: Relative expanded uncertainty (W (%)) of sensor calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logarithmic scale

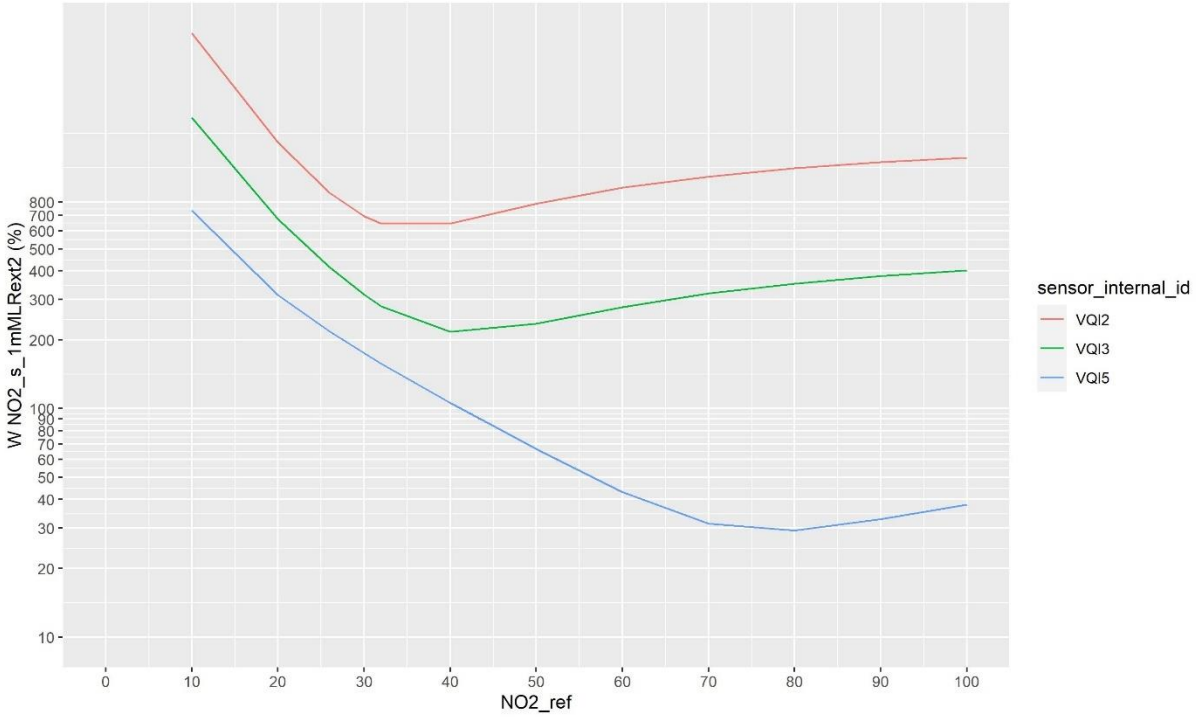


Figure 62: Citytech 3E50 NO_2 sensor: Relative expanded uncertainty (W (%)) of sensors calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logaritmic scale.

Table 22: Citytech 3E50 NO_2 sensor: Relative expanded uncertainty of sensors calibrated with extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO_2 hourly reference concentrations of 100 µg/m³ (LAT), 140 µg/m³ (UAT) and 200 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLRext2	VQI2	100	108.90	432.31	891.64
NO_2_s_1mMLRext2	VQI3	100	53.39	156.38	330.49
NO_2_s_1mMLRext2	VQI5	100	14.19	10.79	35.65
NO_2_s_1mMLRext2	VQI2	140	108.90	688.46	995.75
NO_2_s_1mMLRext2	VQI3	140	53.39	259.69	378.75
NO_2_s_1mMLRext2	VQI5	140	14.19	30.59	48.17
NO_2_s_1mMLRext2	VQI2	200	108.90	1072.69	1078.20
NO_2_s_1mMLRext2	VQI3	200	53.39	414.66	418.08
NO_2_s_1mMLRext2	VQI5	200	14.19	60.29	61.94

Table 23: Citytech 3E50 NO_2 sensor: Relative expanded uncertainty of sensors calibrated with extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO_2 daily reference concentrations of 26 µg/m³ (LAT), 32 µg/m³ (UAT) and 40 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLRext2	VQI2	26	103.23	-49.08	879.26
NO_2_s_1mMLRext2	VQI3	26	42.24	-33.75	415.93
NO_2_s_1mMLRext2	VQI5	26	10.90	-26.06	217.25
NO_2_s_1mMLRext2	VQI2	32	103.23	5.03	645.96
NO_2_s_1mMLRext2	VQI3	32	42.24	-15.08	280.33
NO_2_s_1mMLRext2	VQI5	32	10.90	-22.68	157.27
NO_2_s_1mMLRext2	VQI2	40	103.23	77.17	644.45
NO_2_s_1mMLRext2	VQI3	40	42.24	9.81	216.83
NO_2_s_1mMLRext2	VQI5	40	10.90	-18.18	105.98

Table 24: Citytech 3E50 NO_2 sensor: Parameters of orthogonal regression of hourly and daily sensor data calibrated with extended multiple linear regression (NO2_S_1mMLRext2) versus reference NO_2

		hourly values		daily values	
	ID	slope	intercept (µg/m³)	slope	intercept (µg/m³)
NO_2_s_1mMLRext2	VQI2	7.40	-208.06	10.02	-283.55
NO_2_s_1mMLRext2	VQI3	3.58	-101.89	4.11	-114.66
NO_2_s_1mMLRext2	VQI5	1.49	-38.71	1.56	-40.68

4.3.6 Conclusions

There is almost no correlation ($R^2 \leq 0.07$) between the reference data and the sensor data calibrated with the parameters from MLR without O_3 (*NO2_s_1mMLR2*). Adding O_3 to the MRL function is necessary to obtain some correlation between the reference data and the calibrated sensor data (*NO2_s_1mMLRext2*).

After calibration with the parameters from the MLR with O_3 we see less scatter in the ratios of the sensor data (*NO2_s_1mMLRext2*) versus the reference data in relation to

temperature, relative humidity and O_3. For sensor VQI2 there seems to be a shift in the calibrated sensor data from October on: the ratios of sensor VQI2 are mainly negative before October and positive from October on. We see this shift also in the plots of the ratios in relation to relative humidity, temperature and O_3: the ratios for this sensor become positive with higher relative humidity, lower temperature and lower O_3 concentrations. Calibration with the parameters from the MLR with O_3 leads to negative mean biases in the sensor data *NO2_s_1mMLRext2* (between -28 and -21 µg/m^3*)*. The absolute between sensor uncertainty after calibration is 34 µg/m^3. In relation with the large underestimation of the calibrated sensor data in comparison to the reference data, this leads to a very high relative between sensor uncertainty (652 %). The R^2 is 0.7 for sensor VQI5 after calibration, but is much smaller for the sensors VQI2 and VQI3 (0.24).

VQI5 is the only sensor for which the expanded uncertainty of the hourly sensor data is ≤ 75% at the LV (200 µg/m^3), the UAT (140 µg/m^3) and the LAT (100 µg/m^3). The expanded uncertainty of the daily sensor data is never ≤ 75 % at the LV (40 µg/m^3), the UAT (32 µg/m^3) and the LAT (26 µg/m^3).

Field Evaluation
Membrapor C1 NO_2 sensor

Manufacturer: Membrapor

Link to website manufacturer

Link to test protocol

5 Membrapor C1 NO_2 sensor

5.1 Validation and data coverage

Both negative and positive peaks occur in the raw sensor data. When these peaks occurred after a restart of the measurements, they were marked as invalid. Other peaks were marked as suspicious when they were remarkable higher of lower than the values of the other sensors. Due to unstable measurements, the data of VQK1 were marked as suspicious between January 30, 2020 until March 10, 2020.

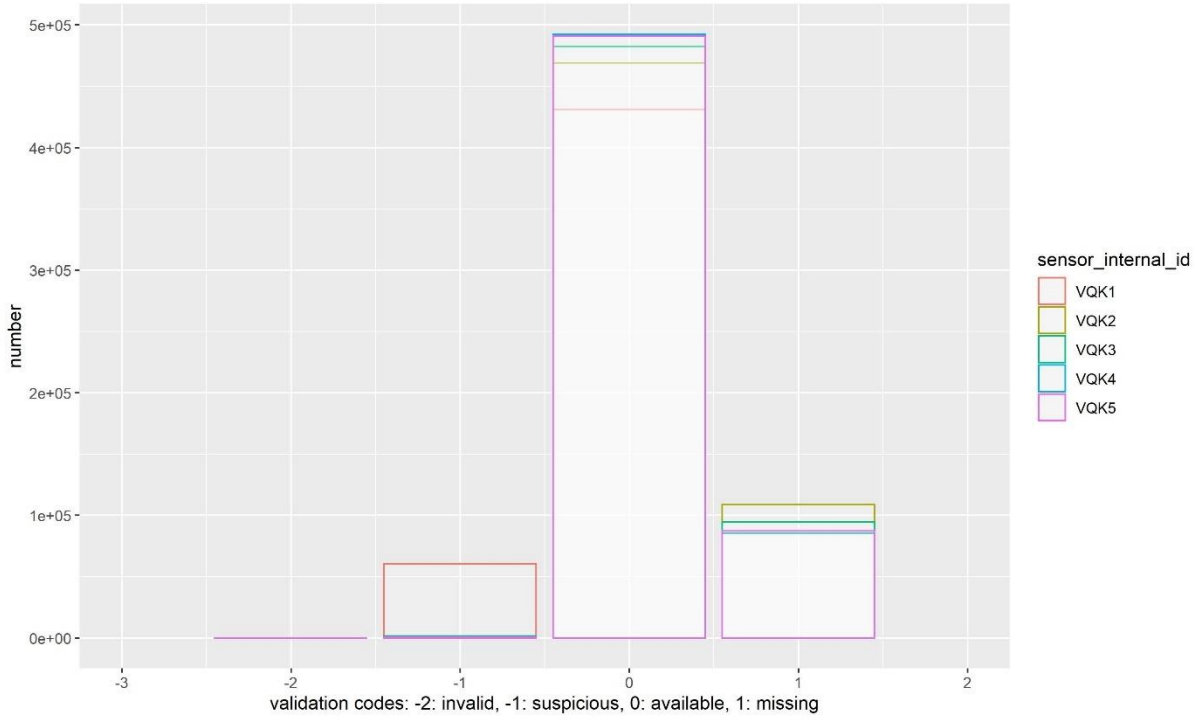


Figure 63: Membrapor C1 NO_2 sensor: Number sensor minute values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 25: Membrapor C1 NO_2 sensor: Number sensor minute values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQK1	3	60725	430825	87327	74
VQK2	6	840	469249	108785	81
VQK3	29	1619	482657	94575	83
VQK4	28	755	492518	85579	85
VQK5	4	686	490910	87280	85

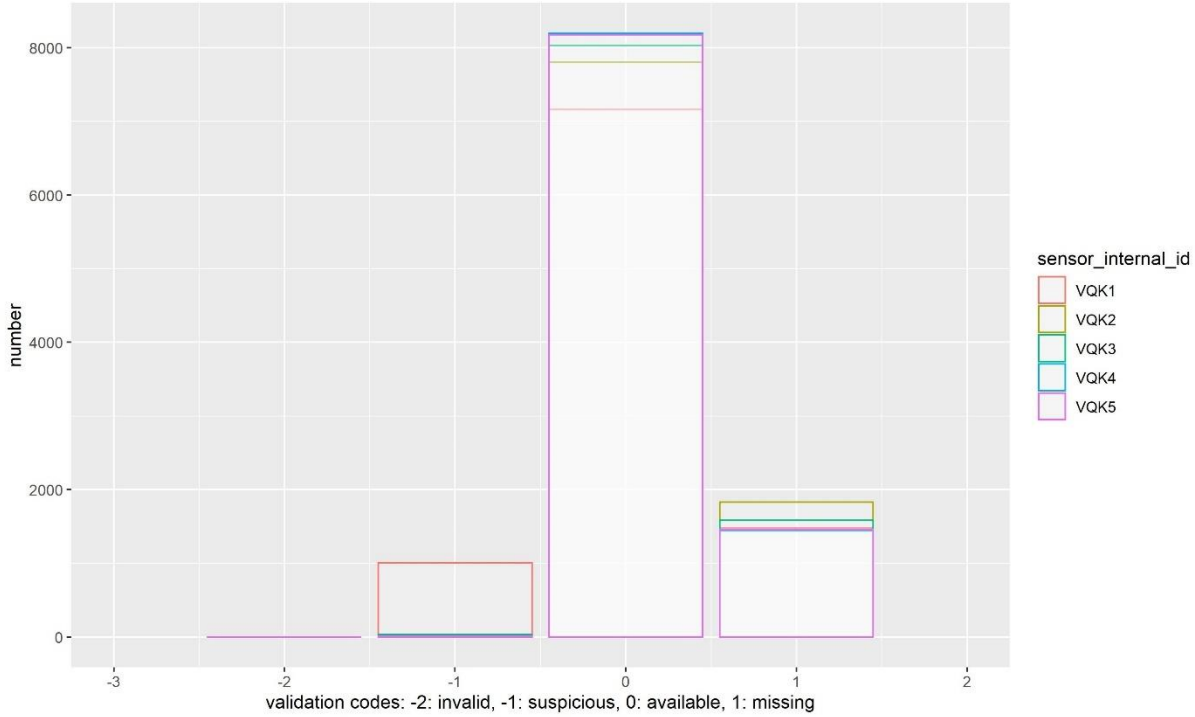


Figure 64: Membrapor C1 NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 26: Membrapor C1 NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQK1	0	1011	7158	1479	74
VQK2	0	15	7801	1832	81
VQK3	0	31	8032	1585	83
VQK4	0	13	8196	1439	85
VQK5	0	11	8177	1460	85

5.2 Uncalibrated sensor data and sensor data calibrated with parameters from linear regression

5.2.1 Calibration parameters

As can be seen in the table with the descriptive parameters, there is almost no correlation ($R^2 \leq 0.04$) between the uncalibrated sensor data and the reference data. Due to the low correlation, the parameters of the linear regression are not well defined. Therefore, the parameters of LR are not calculated nor used for this sensor type.

5.2.2 Comparison sensor versus reference

5.2.2.1 Time plot and scatter plots of hourly values

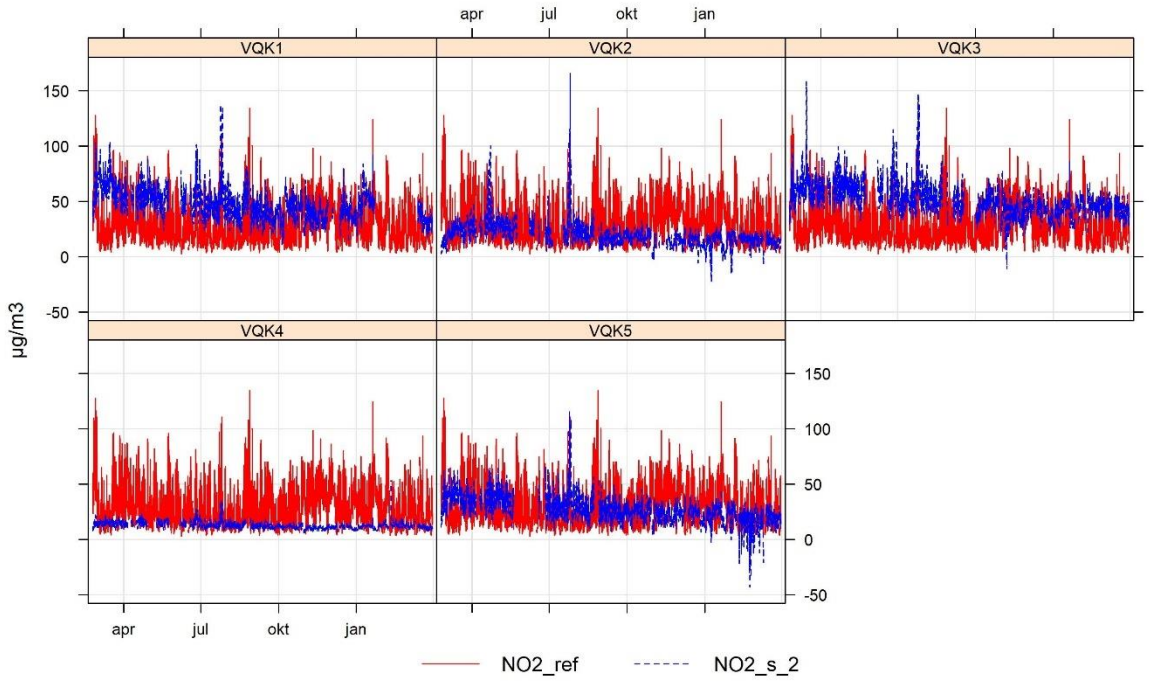


Figure 65: Membrapor C1 NO_2 sensor: Time plot uncalibrated sensor hourly values and reference values (µg/m³)

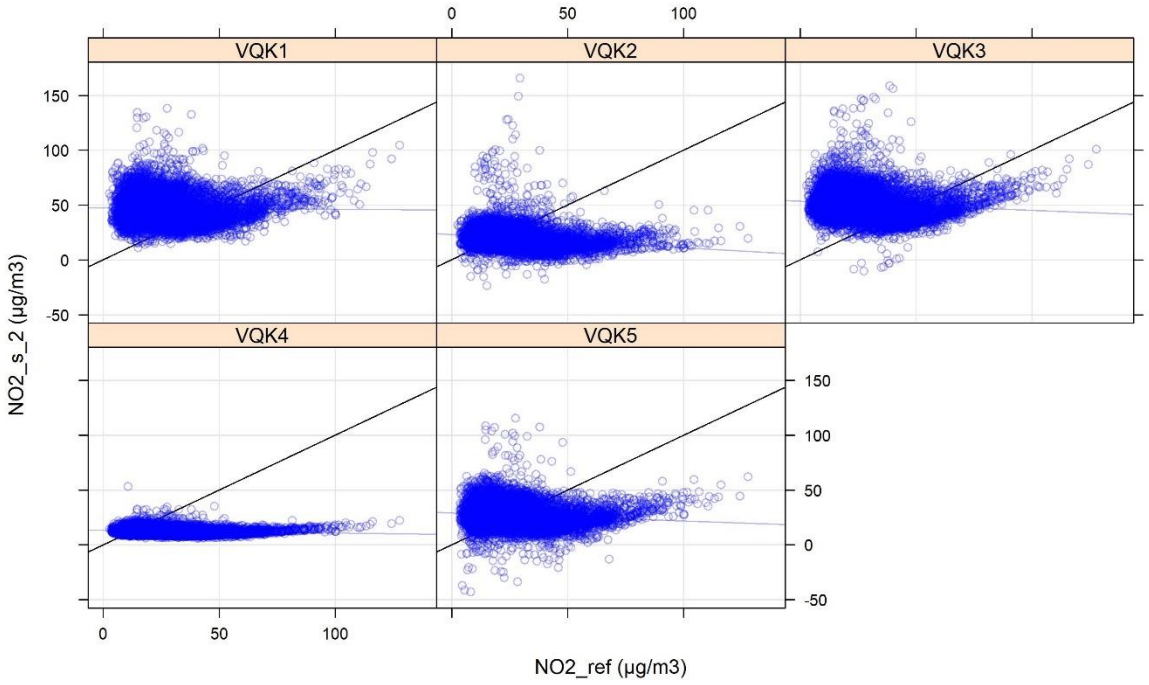


Figure 66: Membrapor C1 NO_2 sensor: Scatter plot of uncalibrated sensor hourly values versus reference values (µg/m3)

5.2.2.2 Ratio of hourly sensor values versus reference values

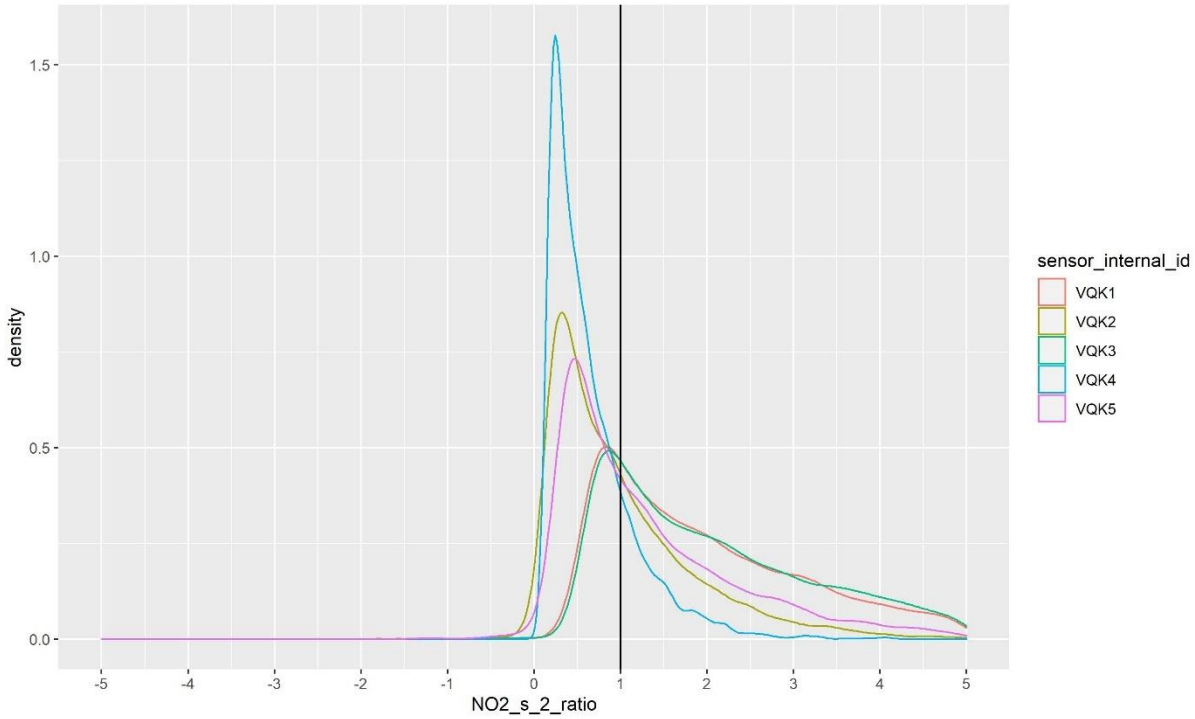


Figure 67: Membrapor C1 NO_2 sensor: Density plot of uncalibrated ratio sensor hourly values versus reference values

5.2.3 Influence of time, temperature, relative humidity and O_3

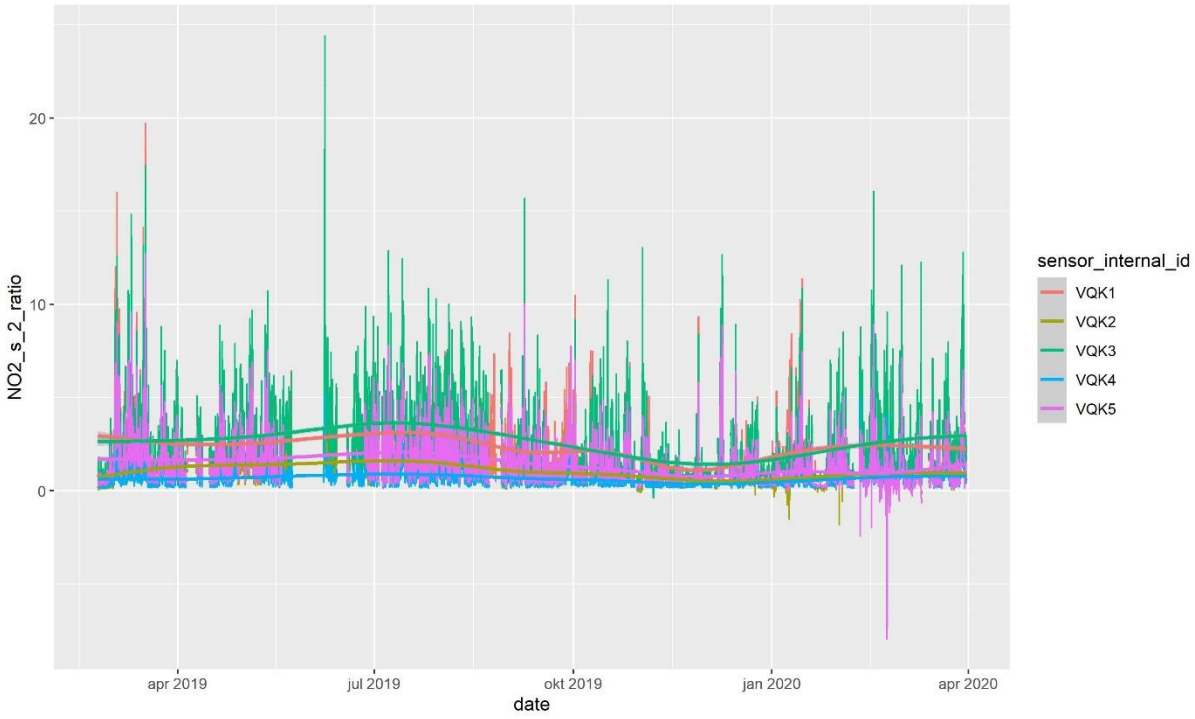


Figure 68: Membrapor C1 NO_2 sensor: Time plot ratio sensor hourly values versus reference values (µg/m³)

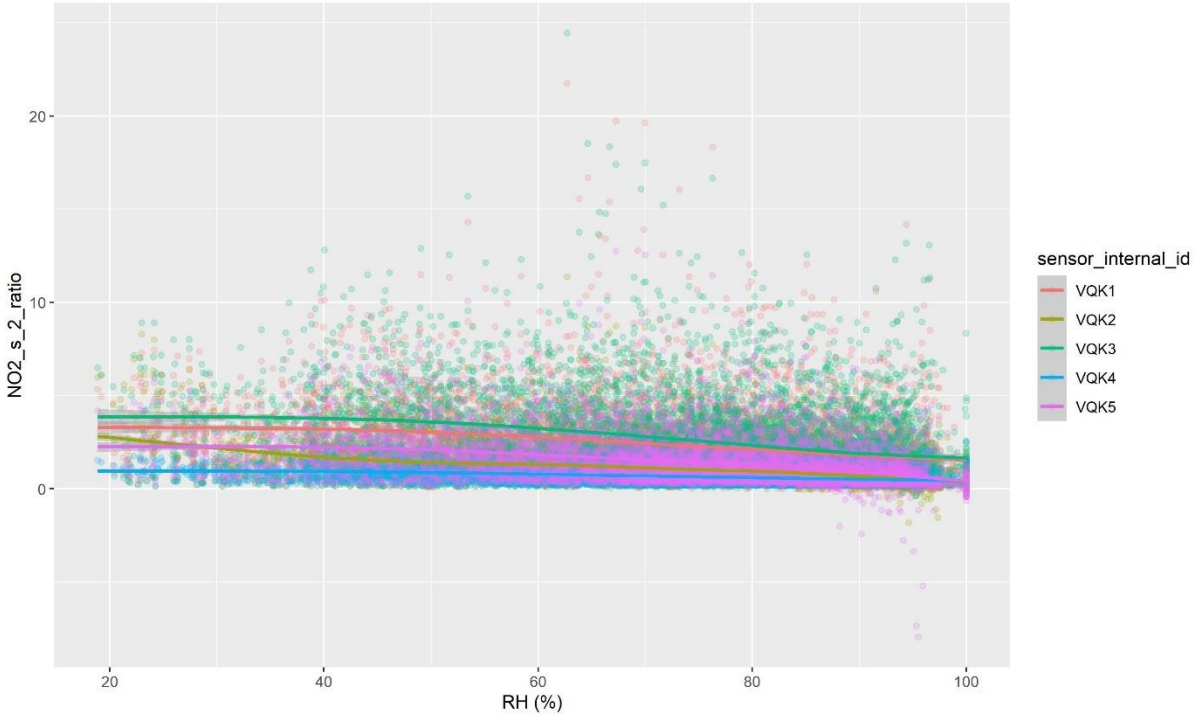


Figure 69: Membrapor C1 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to relative humidity (%)

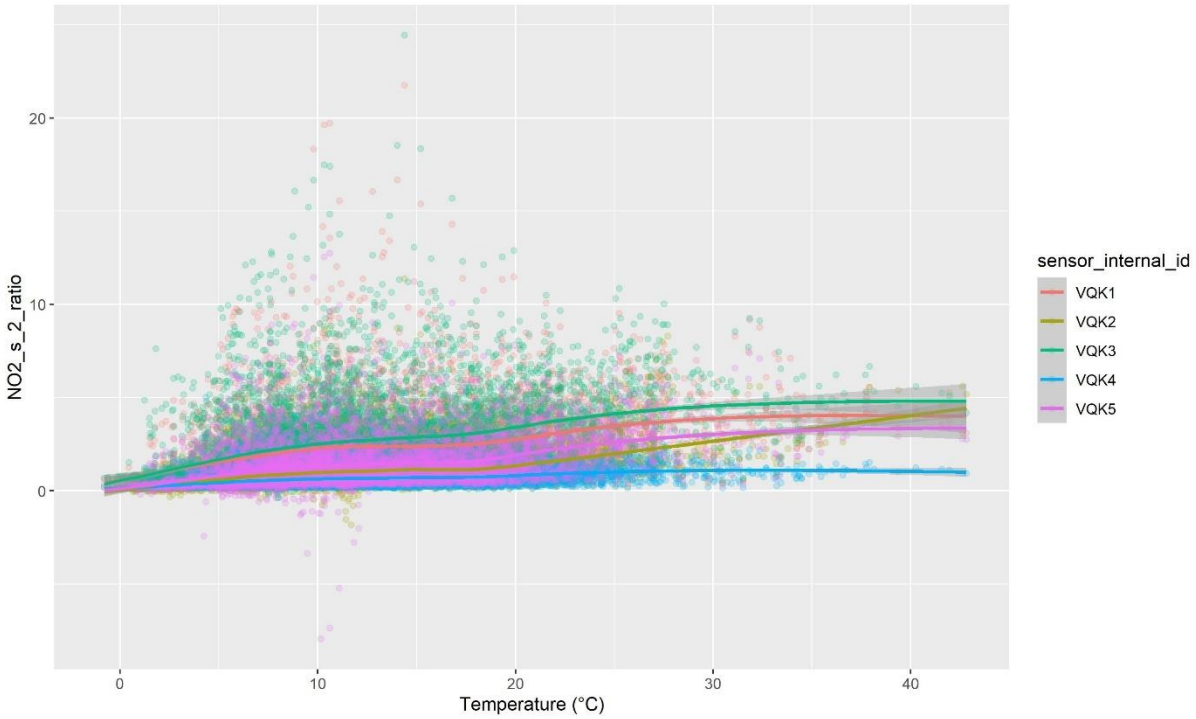


Figure 70: Membrapor C1 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to temperature (°C)

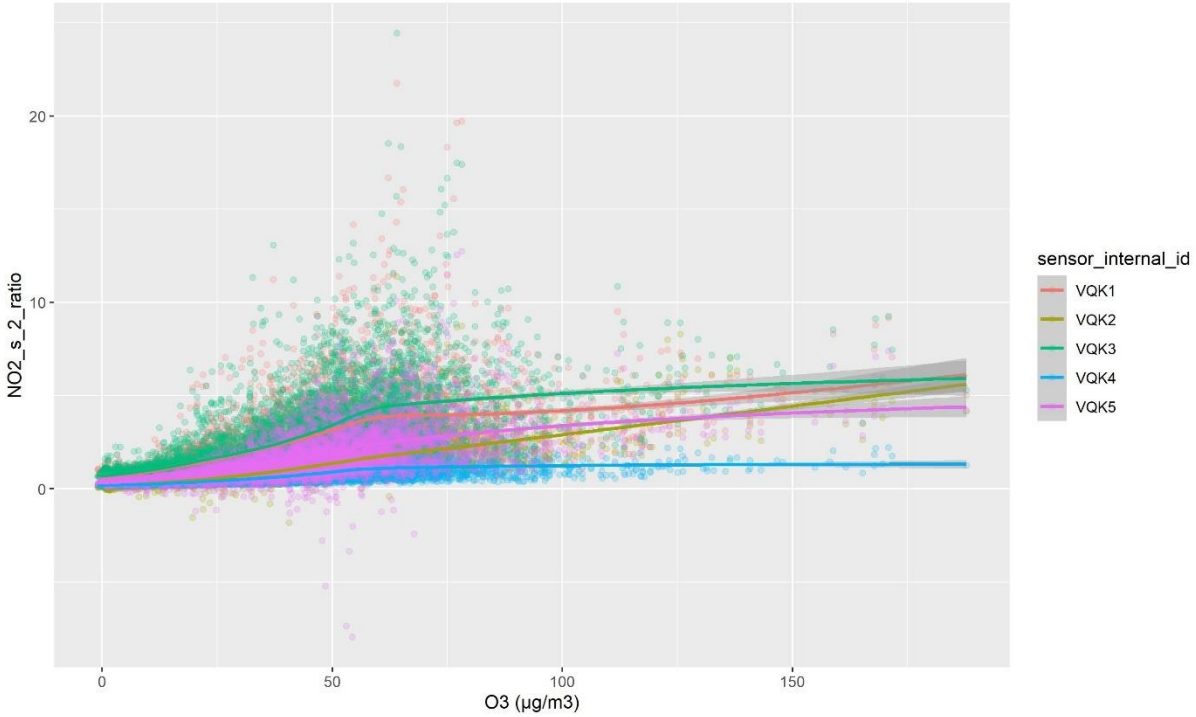


Figure 71: Membrapor C1 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to O_3 (µg/m³)

5.2.4 Descriptive parameters

Table 27: Membrapor C1 NO_2 sensor: Descriptive parameters for uncalibrated sensors. ID: sensor idea, n: number of values, R^2: coefficient of determination, Ubs: between sampler uncertainty

		Evaluation				
	ID	n	mean bias (µg/m³)	R^2	u_{bs} (µg/m³)	u_{bs} (%)
NO_2_s_2	VQK1	6801	17.52	0.00		
NO_2_s_2	VQK2	7372	-9.88	0.04		
NO_2_s_2	VQK3	7583	21.24	0.01		
NO_2_s_2	VQK4	7742	-16.77	0.02		
NO_2_s_2	VQK5	7725	-2.76	0.01		
NO_2_s_2	all	37223			16.65	53.73

5.2.5 Relative expanded uncertainty

The calculation of the relative expanded uncertainty according to the Guidance of of Equivalence is based on the linear regression of the sensor data versus the reference data. As there is almost no correlation between the sensor data and the reference data, this calculation is not executed.

5.2.6 Conclusions

There is no or only very little correlation between the uncalibrated sensor data (*NO2_s_2*) and the reference data ($R^2 \leq 0.04$). The mean biases between the sensor data and the reference data are very different (between -17 and 21 µg/m^3) for the individual sensors.

We see no real drift of the sensor data over time. In winter the ratios seem smaller. The ratios versus the reference method are mostly positive, only at the end we see some negative ratios for some sensors.

The patterns of the ratio plots of sensor data versus the reference data are not so clear in relation to relative humidity. The ratios increase when temperature and O_3 increase. For sensor VQK4 the increase of the ratios is less clear.

As there is no or very little correlation between the sensor data and the reference data, a calibration with linear regression parameters based on the first month of field data is not executed.

5.3 Sensor data calibrated with parameters from multiple linear regression

5.3.1 Calibration parameters

Table 28: Membrapor C1 NO_2 sensor: Parameters from multiple linear regression (including NO_2 reference measurements (NO2_ref), temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	T	RH
VQK1	57.9	-0.11	0.33	0.07*
VQK2	43.1	-0.18	-0.07	-0.20
VQK3	73.4	-0.10	0.15*	-0.13
VQK4	22.2	-0.03	-0.06	-0.08
VQK5	61.5	-0.14	-0.31	-0.22

*:Variable not significant at 0.05 significance level

Table 29: Membrapor C1 NO_2 sensor: Parameters from extended multiple linear regression (including NO_2 reference measurements (NO2_ref), ozone reference measurements (O3_ref) temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	O_3_ref	T	RH
VQK1	-43.9	0.67	0.84	0.95	0.55
VQK2	-18.0	0.29	0.53	0.24	0.08
VQK3	-30.7	0.70	0.87	0.72	0.36
VQK4	1.1	0.14	0.18	0.04	0.01
VQK5	-25.9	0.53	0.74	0.14	0.19

The correlation plots in annex x show high correlation coefficients between the uncalibred sensor data *NO2_s_2* and reference O_3 (R between 0.60 and 0.76). Adding O_3 to the MRL indeed significantly improves the calibrated sensor data. In fact, there is almost no correlation ($R^2 \leq 0.02$) between the reference data and the sensor data calibrated with the MLR parameters without O_3 and therefore we will not discuss these calibrated sensor data *NO2_s_1mMLR2* any further.

5.3.2 Comparison sensor versus reference

5.3.2.1 Time plot and scatter plots of hourly values

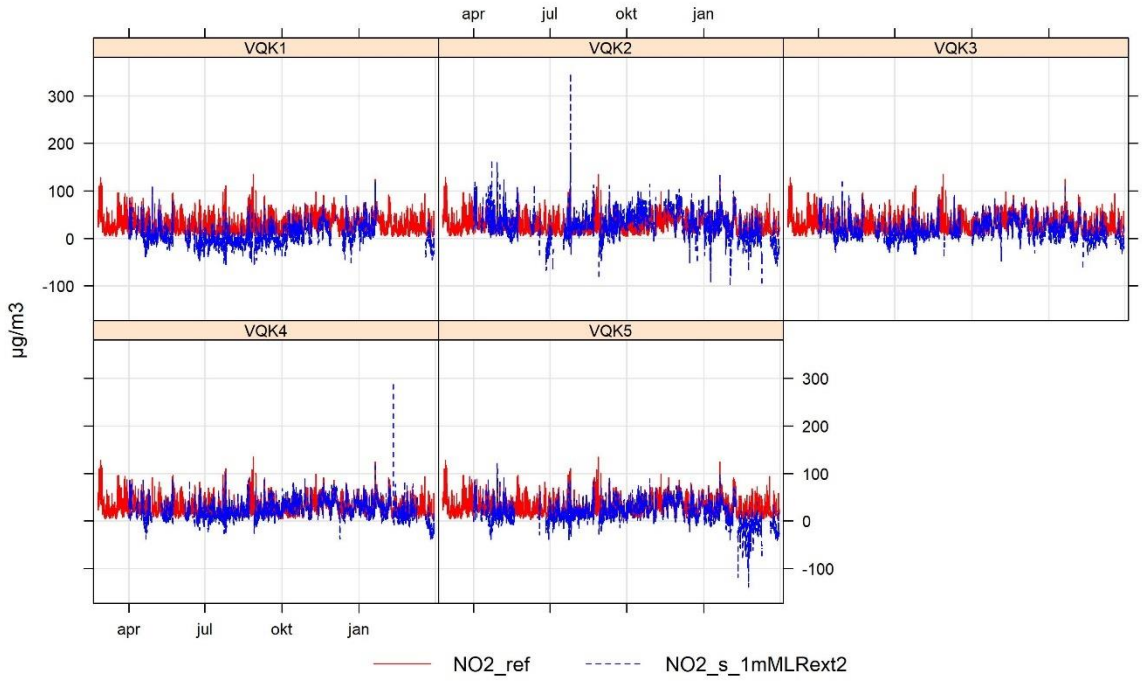


Figure 72: Membrapor C1 NO_2 sensor: Time plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

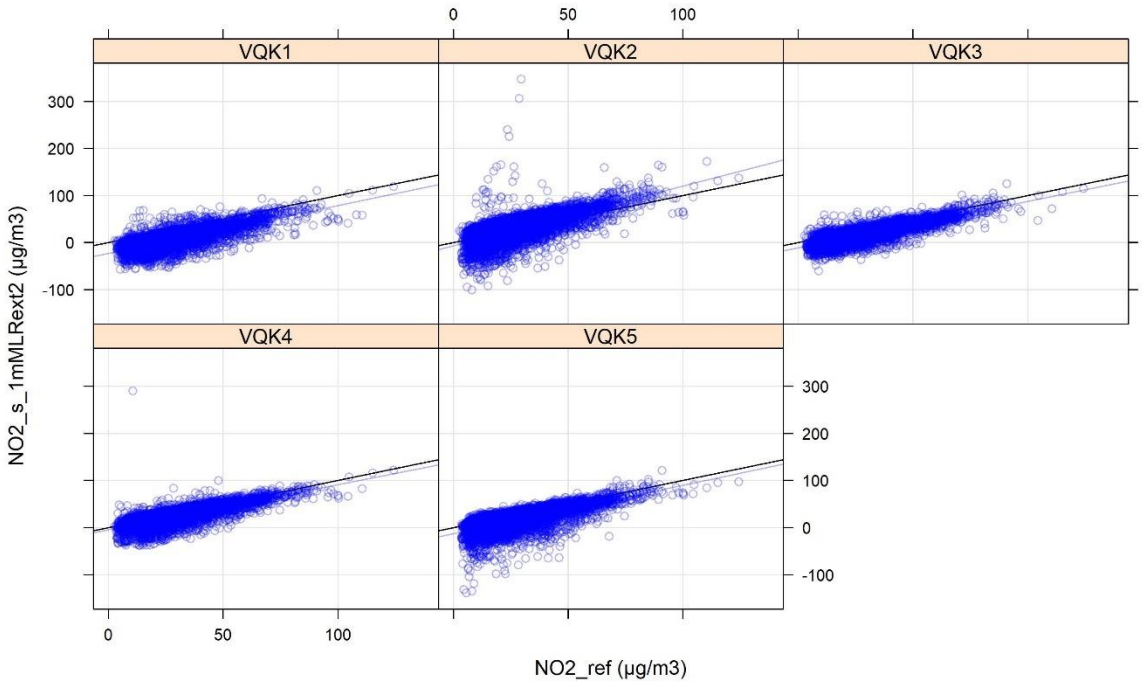


Figure 73: Membrapor C1 NO_2 sensor: Scatter plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

5.3.2.2 Ratio of hourly sensor values versus reference values

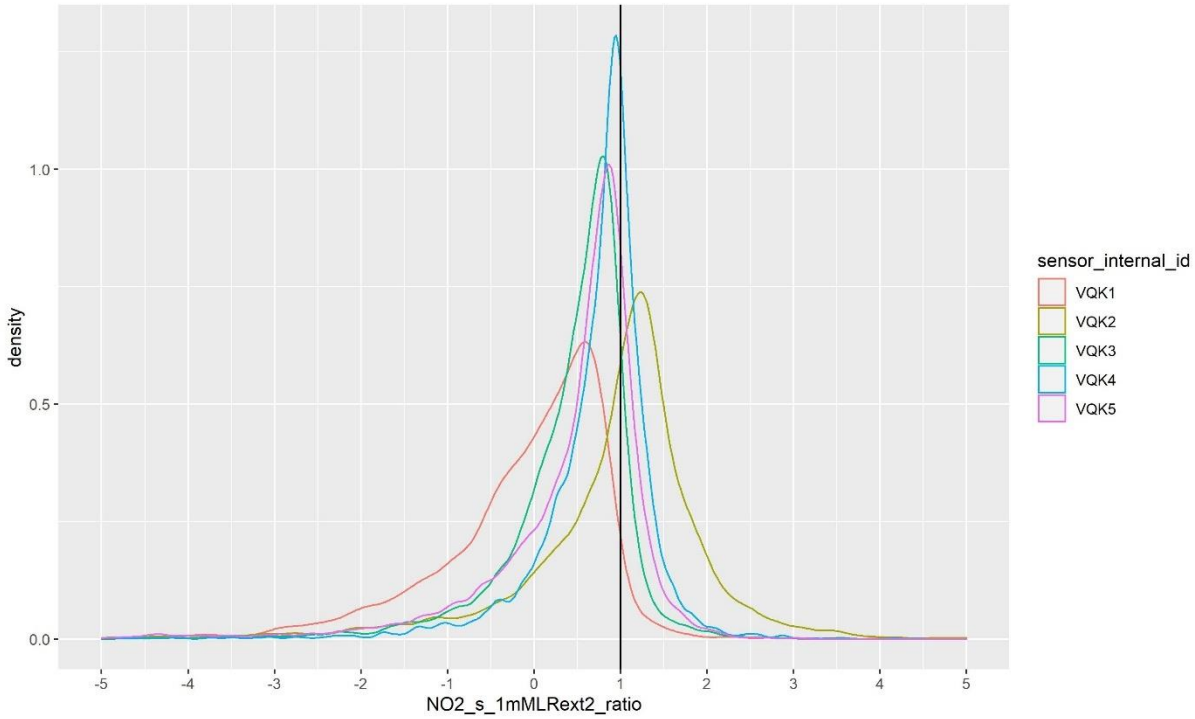


Figure 74: Membrapor C1 NO_2 sensor: Density plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values

5.3.3 Influence of time, temperature, relative humidity and O_3

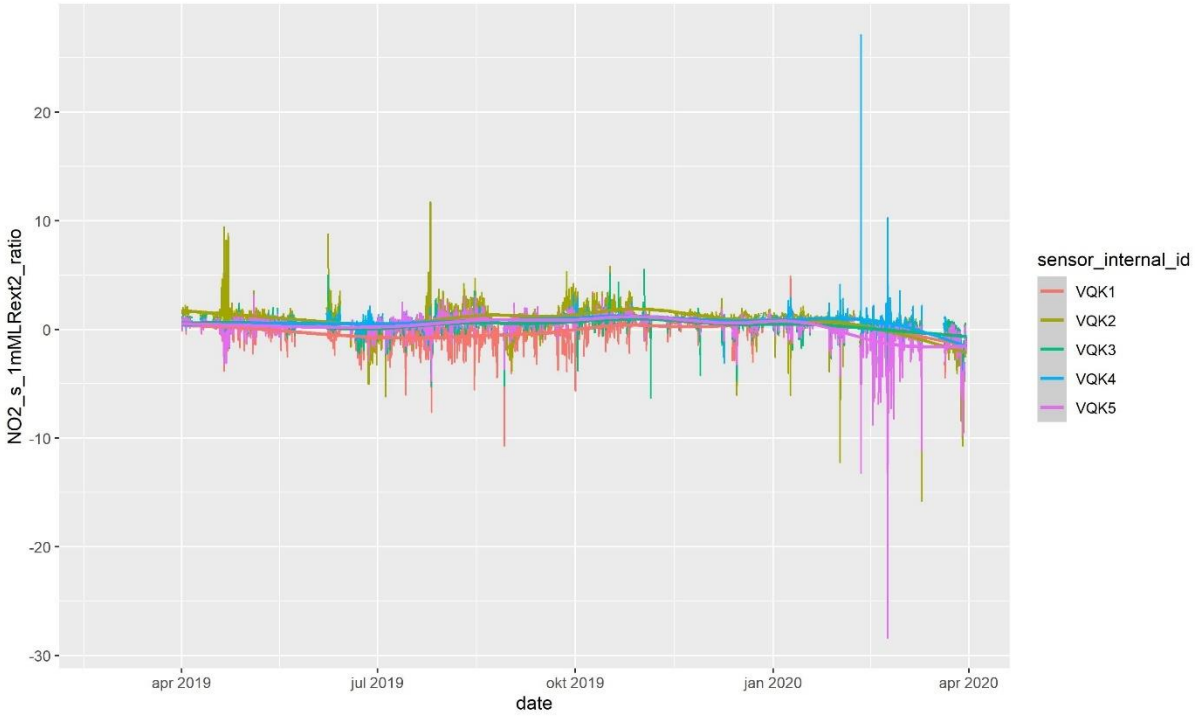


Figure 75: Membrapor C1 NO_2 sensor: Time plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values (µg/m³)

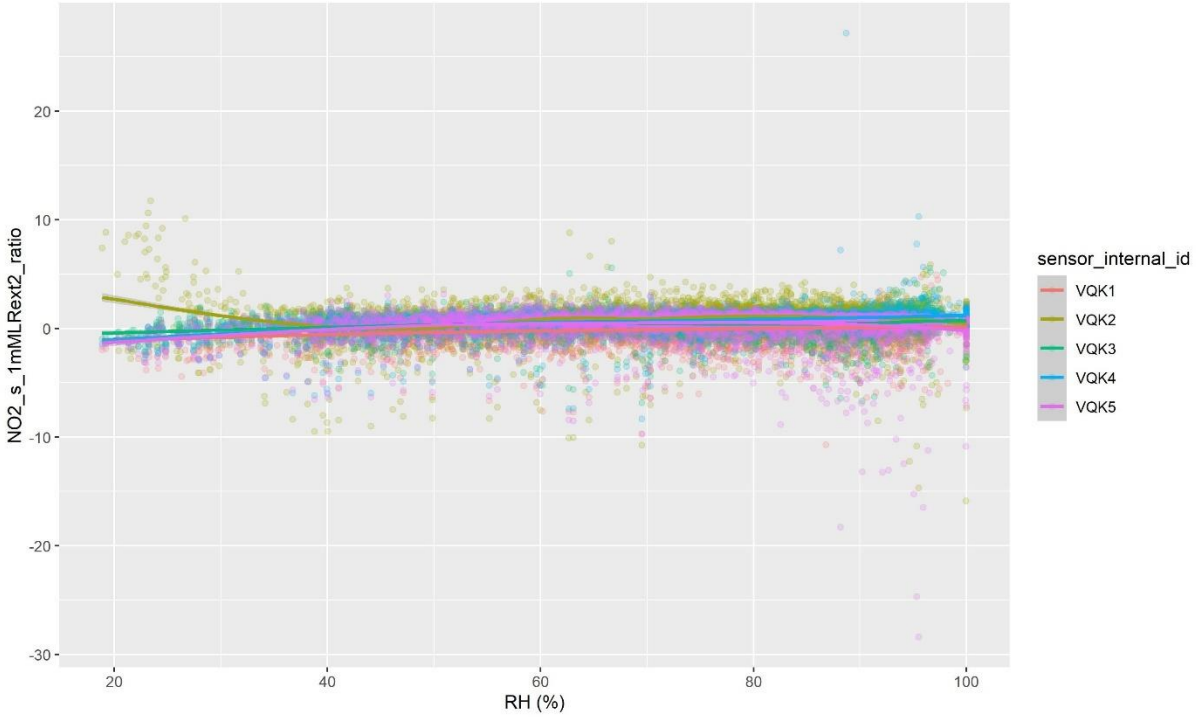


Figure 76: Membrapor C1 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to relative humidity (%)

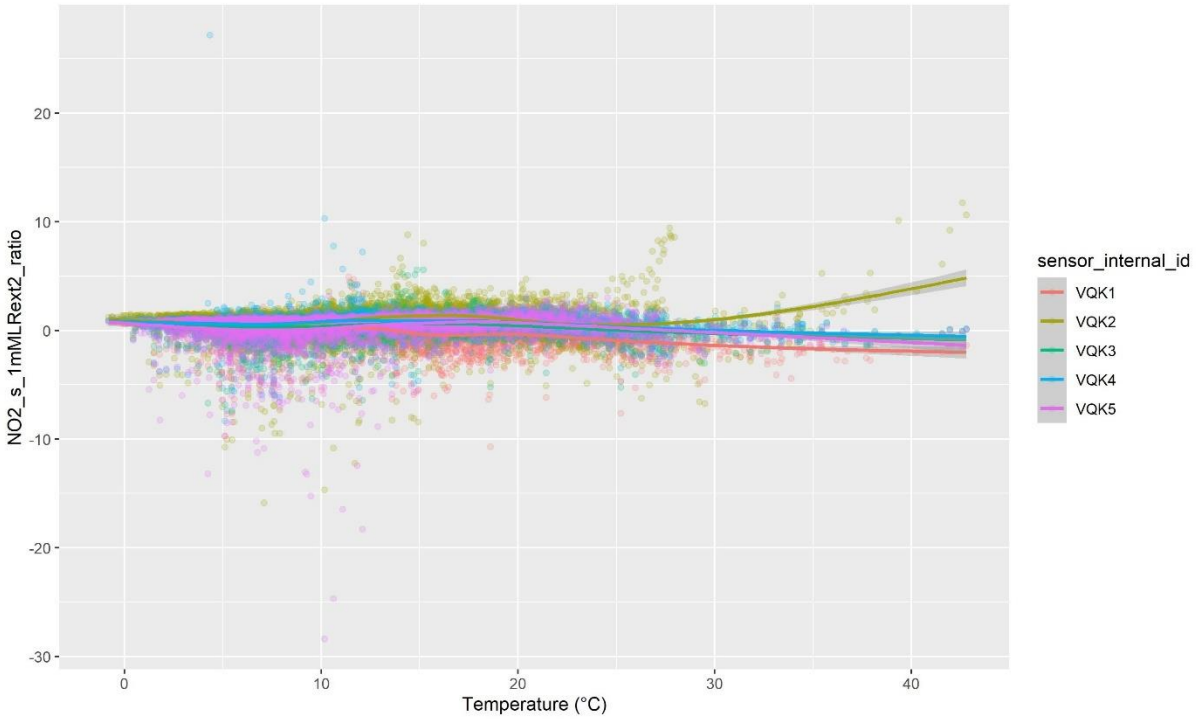


Figure 77: Membrapor C1 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to temperature (°C)

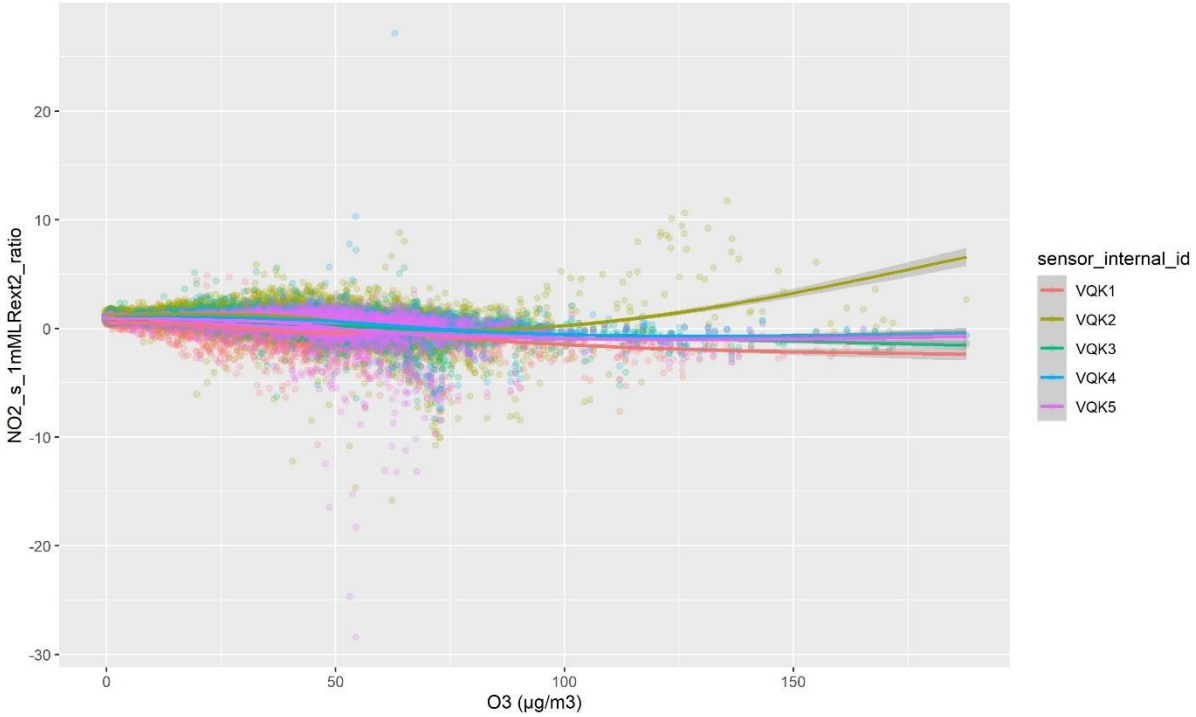


Figure 78: Membrapor C1 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to ozone (µg/m³)

5.3.4 Descriptive parameters

Table 30: Membrapor C1 NO_2 sensor: Descriptive parameters for sensors calibrated with multiple linear regression (NO2_S_A_mMLR2) and extended multiple linear regression (NO2_S_A_mMLRext2). ID: sensor idea, n: number of values, R^2: coefficient of determination, Ubs: between sampler uncertainty

		Calibration		Evaluation				
	ID	n	R^2	n	mean bias (µg/m³)	R^2	u_{bs} (µg/m³)	u_{bs} (%)
NO_2_s_1mMLR2	VQK1	823	0.05	5939	175.72	0.00		
NO_2_s_1mMLR2	VQK2	846	0.31	6478	18.11	0.02		
NO_2_s_1mMLR2	VQK3	846	0.04	6687	124.13	0.01		
NO_2_s_1mMLR2	VQK4	845	0.10	6847	67.50	0.02		
NO_2_s_1mMLR2	VQK5	846	0.14	6829	79.04	0.02		
NO_2_s_1mMLR2	all sensors			32780			84.75	70.45
NO_2_s_1mMLRext2	VQK1	714	0.79	5516	-22.46	0.57		
NO_2_s_1mMLRext2	VQK2	737	0.77	6166	0.64	0.50		
NO_2_s_1mMLRext2	VQK3	737	0.77	6248	-11.59	0.69		
NO_2_s_1mMLRext2	VQK4	736	0.91	6404	-5.78	0.63		
NO_2_s_1mMLRext2	VQK5	737	0.89	6387	-12.13	0.52		
NO_2_s_1mMLRext2	all sensors			30721			18.22	97.63

5.3.5 Relative expanded uncertainty

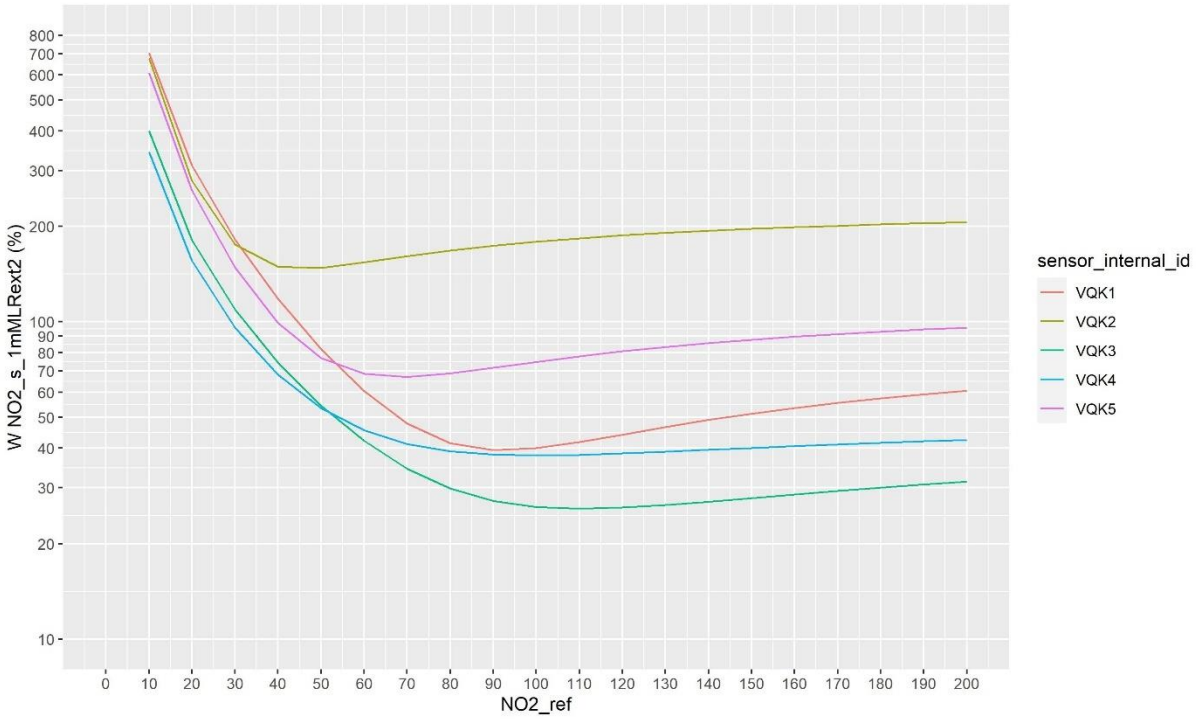


Figure 79: Membrapor C1 NO_2 sensor: Relative expanded uncertainty (W (%)) of sensor calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logarithmic scale

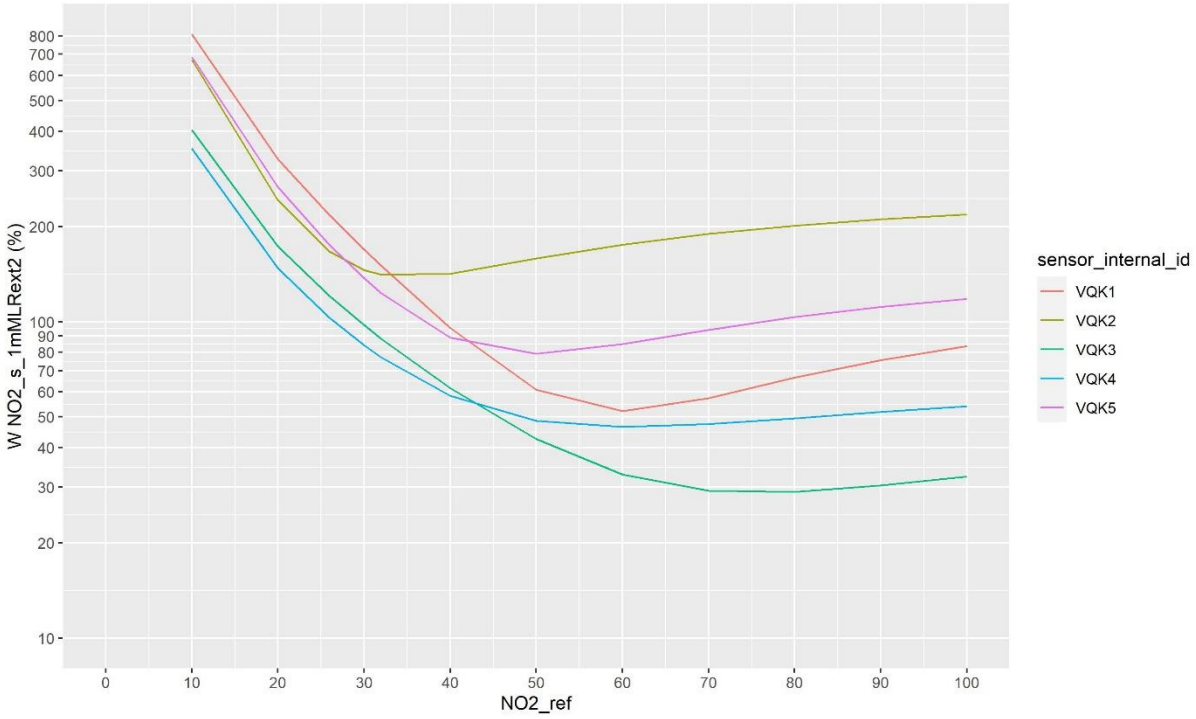


Figure 80: Membrapor C1 NO_2 sensor: Relative expanded uncertainty (W (%)) of sensors calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logaritmic scale.

Table 31: Membrapor C1 NO_2 sensor: Relative expanded uncertainty of sensors calibrated with extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO_2 hourly reference concentrations of 100 µg/m³ (LAT), 140 µg/m³ (UAT) and 200 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLRext2	VQK1	100.00	16.48	11.29	39.96
NO_2_s_1mMLRext2	VQK2	100.00	26.21	85.52	178.90
NO_2_s_1mMLRext2	VQK3	100.00	11.92	5.30	26.09
NO_2_s_1mMLRext2	VQK4	100.00	13.36	13.46	37.93
NO_2_s_1mMLRext2	VQK5	100.00	19.21	32.08	74.79
NO_2_s_1mMLRext2	VQK1	140.00	16.48	30.12	49.05
NO_2_s_1mMLRext2	VQK2	140.00	26.21	133.05	193.73
NO_2_s_1mMLRext2	VQK3	140.00	11.92	14.77	27.11
NO_2_s_1mMLRext2	VQK4	140.00	13.36	24.21	39.50
NO_2_s_1mMLRext2	VQK5	140.00	19.21	56.85	85.72
NO_2_s_1mMLRext2	VQK1	200.00	16.48	58.36	60.65
NO_2_s_1mMLRext2	VQK2	200.00	26.21	204.34	206.02
NO_2_s_1mMLRext2	VQK3	200.00	11.92	28.97	31.33
NO_2_s_1mMLRext2	VQK4	200.00	13.36	40.32	42.48
NO_2_s_1mMLRext2	VQK5	200.00	19.21	94.00	95.94

Table 32: Membrapor C1 NO_2 sensor: Relative expanded uncertainty of sensors calibrated with extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO_2 daily reference concentrations of 26 µg/m³ (LAT), 32 µg/m³ (UAT) and 40 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLRext2	VQK1	26	14.83	-24.00	217.05
NO_2_s_1mMLRext2	VQK2	26	21.54	-2.21	166.54
NO_2_s_1mMLRext2	VQK3	26	9.85	-12.18	120.49
NO_2_s_1mMLRext2	VQK4	26	11.65	-6.55	102.79
NO_2_s_1mMLRext2	VQK5	26	17.79	-14.12	174.69
NO_2_s_1mMLRext2	VQK1	32	14.83	-18.88	150.08
NO_2_s_1mMLRext2	VQK2	32	21.54	6.64	140.86
NO_2_s_1mMLRext2	VQK3	32	9.85	-10.15	88.39
NO_2_s_1mMLRext2	VQK4	32	11.65	-4.04	77.05
NO_2_s_1mMLRext2	VQK5	32	17.79	-8.40	122.96
NO_2_s_1mMLRext2	VQK1	40	14.83	-12.06	95.58
NO_2_s_1mMLRext2	VQK2	40	21.54	18.45	141.79
NO_2_s_1mMLRext2	VQK3	40	9.85	-7.44	61.72
NO_2_s_1mMLRext2	VQK4	40	11.65	-0.70	58.34
NO_2_s_1mMLRext2	VQK5	40	17.79	-0.79	89.03

Table 33: Membrapor C1 NO_2 sensor: Parameters of orthogonal regression of hourly and daily sensor data calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) versus reference NO_2

		hourly values		daily values	
	ID	slope	intercept (µg/m³)	slope	intercept (µg/m³)
NO_2_s_1mMLRext2	VQK1	1.47	-35.79	1.85	-46.19
NO_2_s_1mMLRext2	VQK2	2.19	-33.30	2.48	-40.57
NO_2_s_1mMLRext2	VQK3	1.24	-18.38	1.34	-20.98
NO_2_s_1mMLRext2	VQK4	1.27	-13.40	1.42	-17.42
NO_2_s_1mMLRext2	VQK5	1.62	-29.84	1.95	-38.87

5.3.6 Conclusions

There is almost no correlation ($R^2 \leq 0.02$) between the reference data and the sensor data calibrated with the parameters from MLR without O_3 (*NO2_s_1mMLR2*). Adding O_3 to the MRL is necessary to obtain some correlation between the reference data and the calibrated sensor data (*NO2_s_1mMLRext2*).

After calibration with the parameters from the MLR with O_3 (*NO2_s_1mMLRext 2*) the R^2 varies between 0.50 and 0.69. We see less scatter and no clear patterns in the ratios of the sensor data versus the reference method in relation to temperature, relative humidity and O_3. The ratios of sensor data VQK5 are more negative at the end of the campaing compared to the uncalibrated data. Calibration leads to negative biases (between -22 and -6 µg/m^3) in the sensor data *NO2_s_*1mMLRext2 for all sensors, except for sensor VQK2 where a slightly positive bias (1 µg/m^3) is noticed. The between sensor uncertainty after calibration is 98 %.

The expanded uncertainty of the hourly calibrated sensor data *NO2_s_1mMLRext 2* is ≤ 75 % at the LV (200 µg/m^3), the UAT (140 µg/m^3) and the LAT (100 µg/m^3) for sensors VQK1, VQK3 and VQK4. The expanded uncertainty of the hourly sensor data is also ≤ 75 % at the LAT for sensor VQK5.

The expanded uncertainty of the daily calibrated sensor data *NO2_s_1mMLRext2* is only ≤ 75 % at the LV (40 µg/m^3) for the sensors VQK3 and VQK4.

The expanded uncertainty at the LV, the UAT and the LAT for the hourly and daily sensor data *NO2_s_1mMLR2ext2* is always > 25 %.

Field Evaluation
Membrapor C20 NO_2 sensor

Manufacturer: Membrapor

Link to website manufacturer

Link to test protocol

6 Membrapor C20 NO_2 sensor

6.1 Validation and data coverage

Al lot of negative and positive peaks occur in the raw data. It was not possible to remove these peaks manually, so the these peaks were marked as 'suspicious' automatically when higher than 400 µg/m^3 and lower than -100 µg/m^3.

VQL4 and VQL5 showed these peaks from the beginning. From December on we saw peaks in the data from all sensors. The frequency of occurrence of these peaks in the data of VQL4 and VQL5 increased. When looking at the time plots, we noticed a drop in the data of VQL1 from December 15 2019 on. We also saw a lot of remaining peaks in the data of the other sensors from December on. The data from December 1, 2019 until March 30, 2020 were marked suspicious.

VQL2 and VQL5 were tested in the laboratory, but showed deviations from the other sensors and were therefore not included in the evaluation of the laboratory testing. VQL1 was not included in the laboratory study.

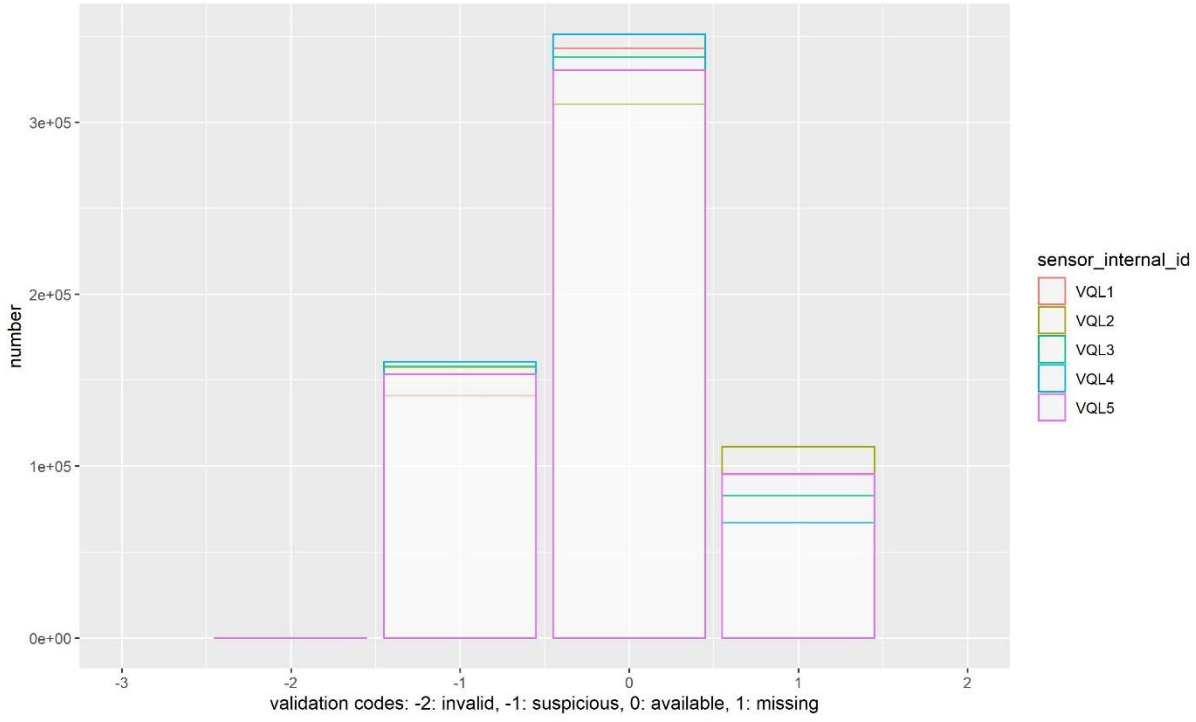


Figure 81: Membrapor C20 NO_2 sensor: Number sensor minute values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 34: Membrapor C20 NO_2 sensor: Number sensor minute values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQL1	0	140884	342950	95046	59
VQL2	0	157305	310565	111010	54
VQL3	0	158169	337814	82897	58
VQL4	0	160589	351182	67109	61
VQL5	0	153283	330305	95292	57

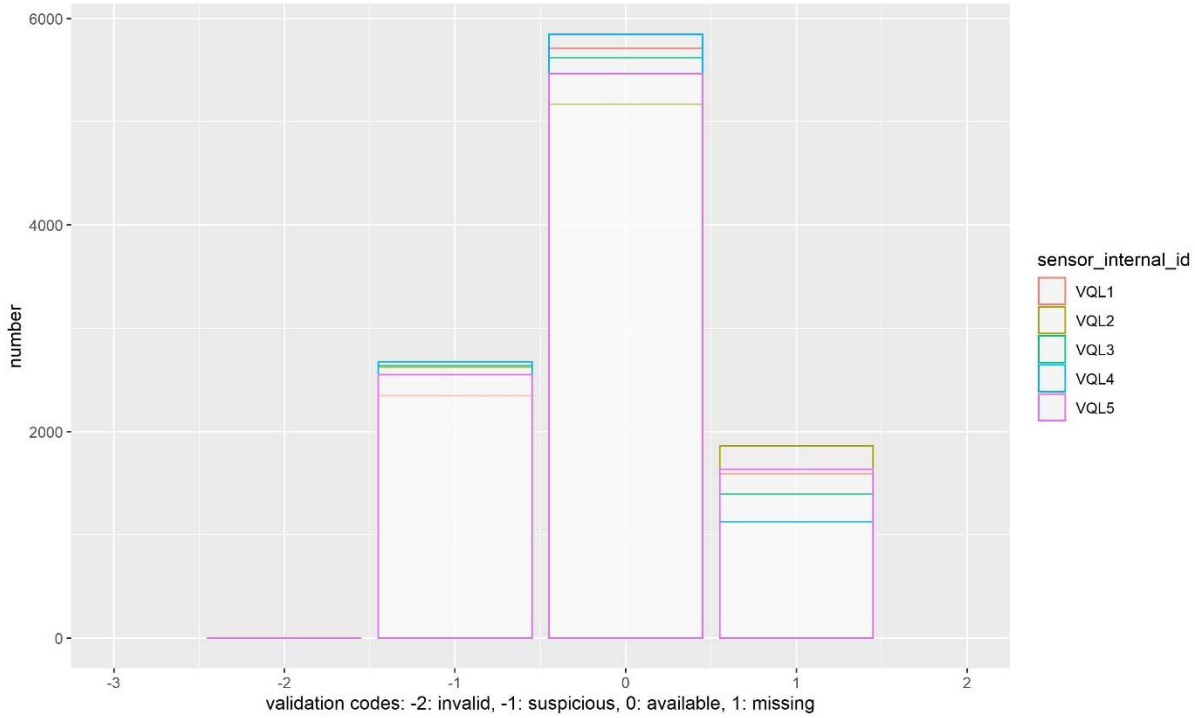


Figure 82: Membrapor C20 NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 35: Membrapor C20 NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQL1	0	2348	5708	1592	59
VQL2	0	2621	5165	1862	54
VQL3	0	2636	5620	1392	58
VQL4	0	2676	5846	1126	61
VQL5	0	2551	5463	1634	57

6.2 Uncalibrated sensor data and sensor data calibrated with parameters from linear regression

6.2.1 Calibration parameters

As can be seen in the table with the descriptive parameters, there is almost no correlation ($R^2 \leq 0.03$) between the uncalibrated sensor data and the reference data. Due to the low correlation, the parameters of the linear regression are not well defined. Therefore, the parameters of LR are not calculated nor used for this sensor type.

6.2.2 Comparison sensor versus reference

6.2.2.1 Time plot and scatter plots of hourly values

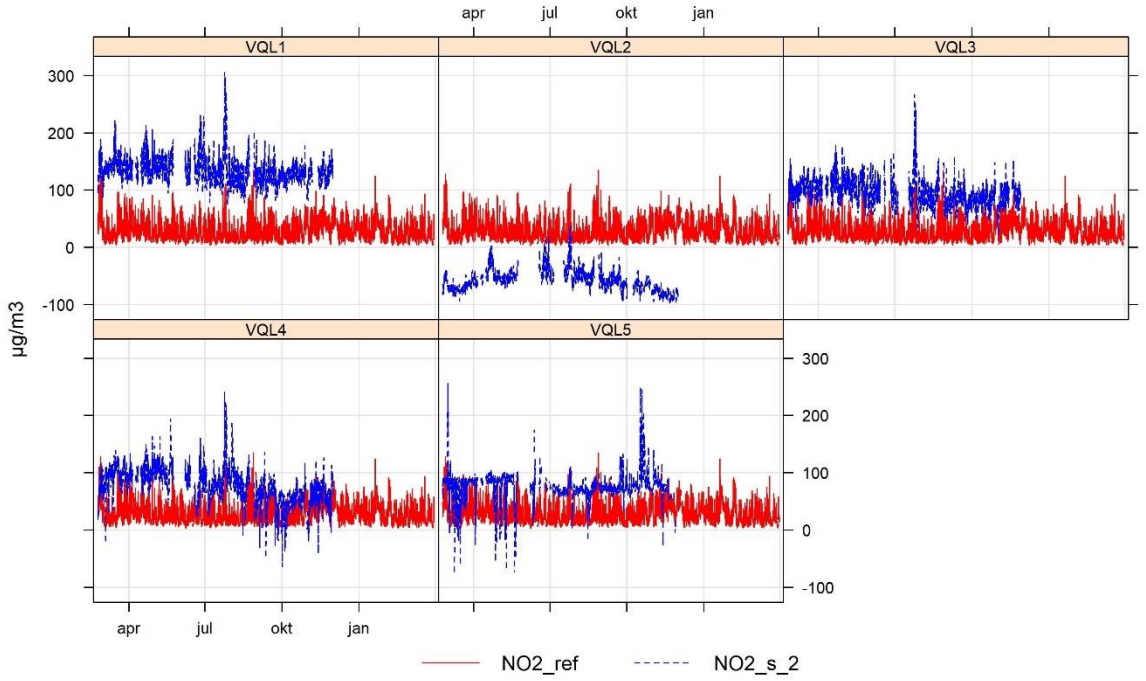


Figure 83: Membrapor C20 NO_2 sensor: Time plot uncalibrated sensor hourly values and reference values (µg/m³)

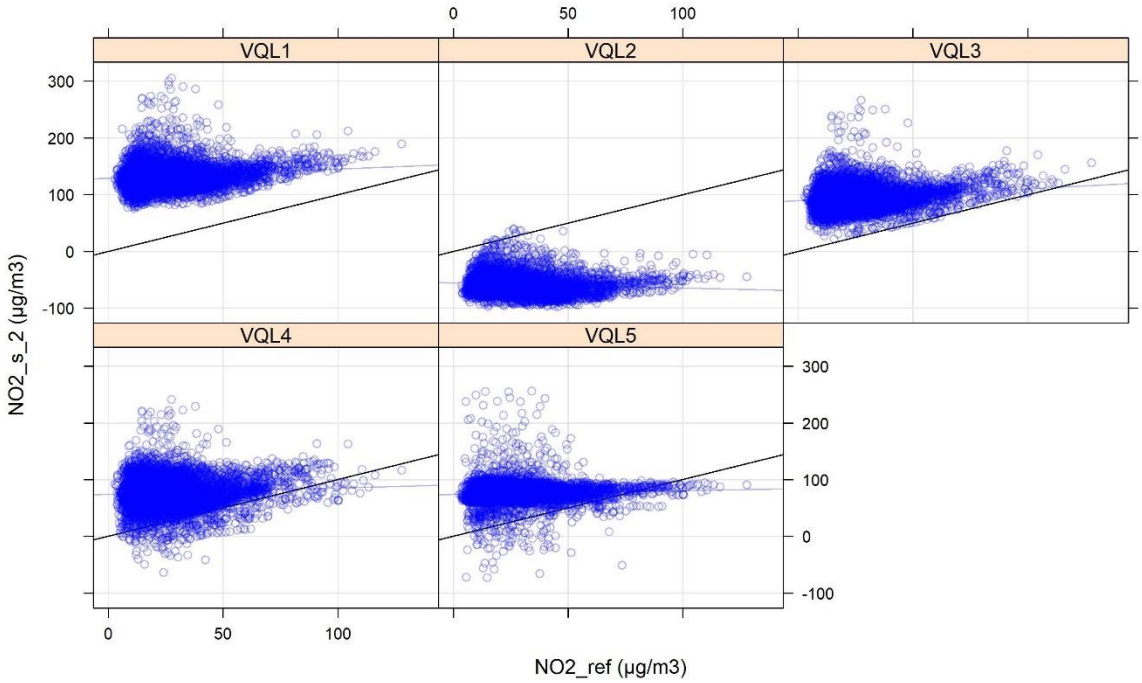


Figure 84: Membrapor C20 NO_2 sensor: Scatter plot of uncalibrated sensor hourly values versus reference values (µg/m³)

6.2.2.2 Ratio of hourly sensor values versus reference values

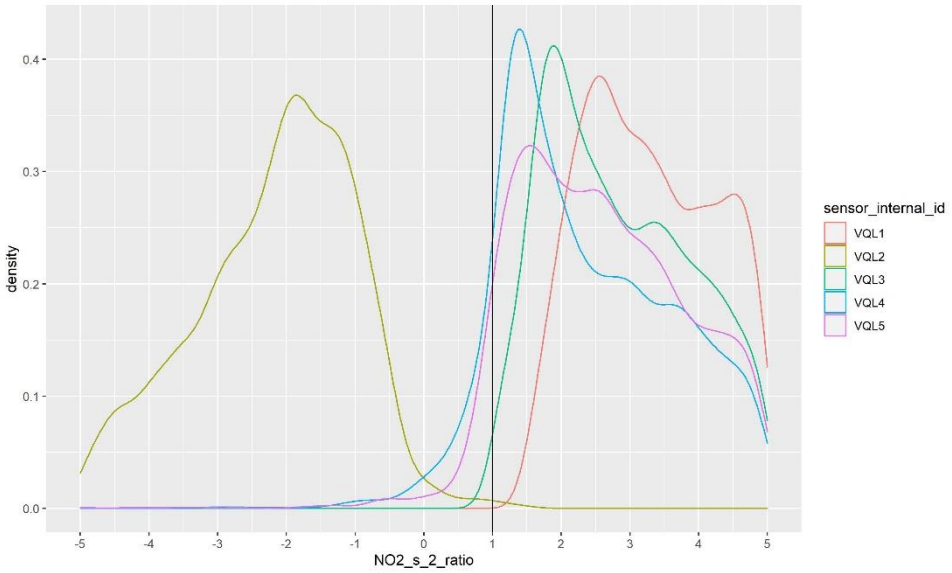


Figure 85: Membrapor C20 NO_2 sensor: Density plot of uncalibrated ratio sensor hourly values versus reference values

6.2.3 Influence of time, temperature, relative humidity and O_3

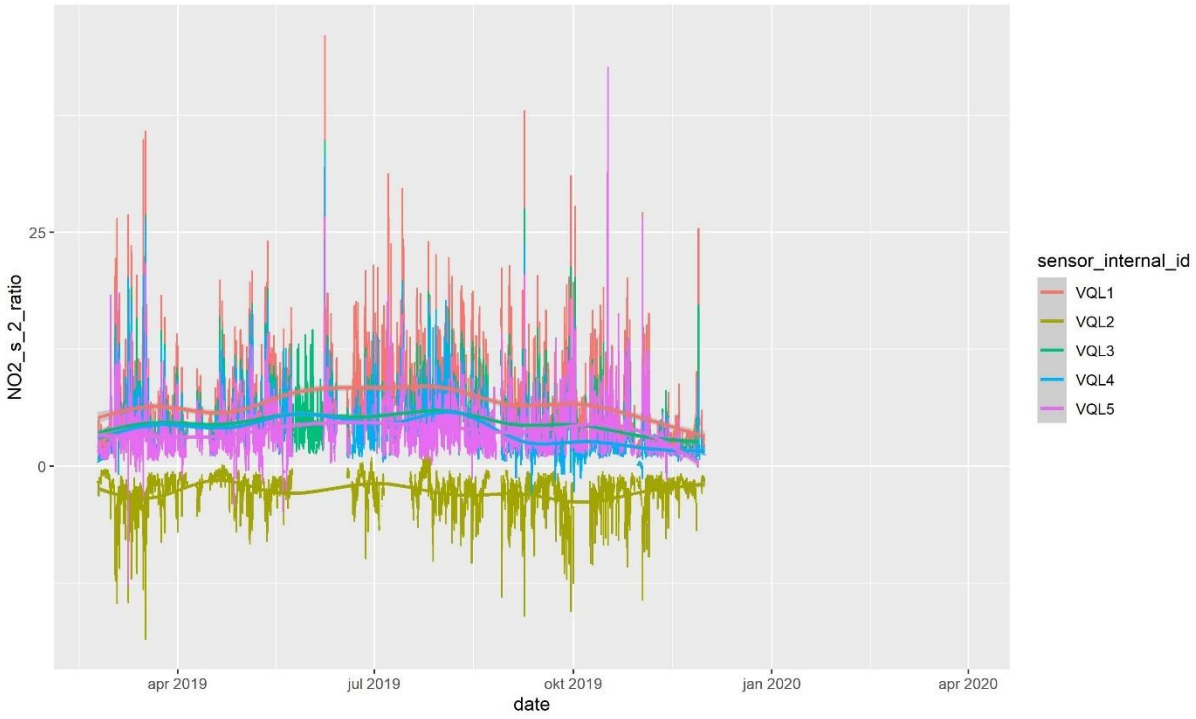


Figure 86: Membrapor C20 NO_2 sensor: Time plot ratio sensor hourly values versus reference values (µg/m³)

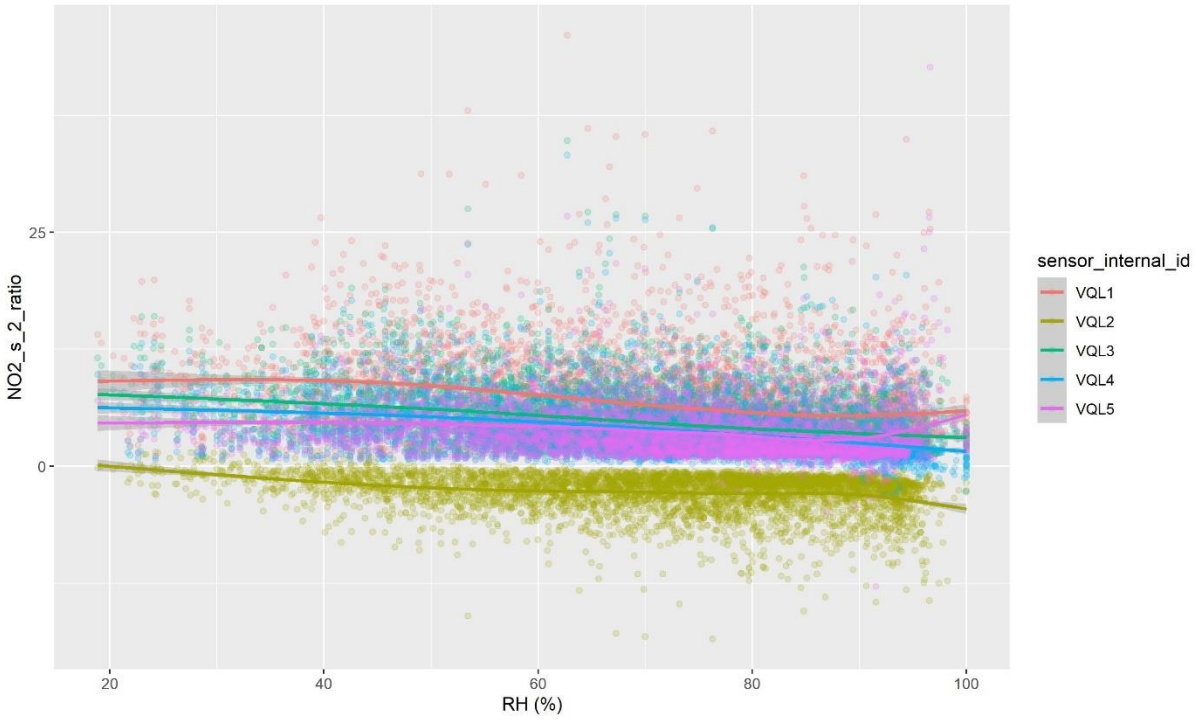


Figure 87: Membrapor C20 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to relative humidity (%)

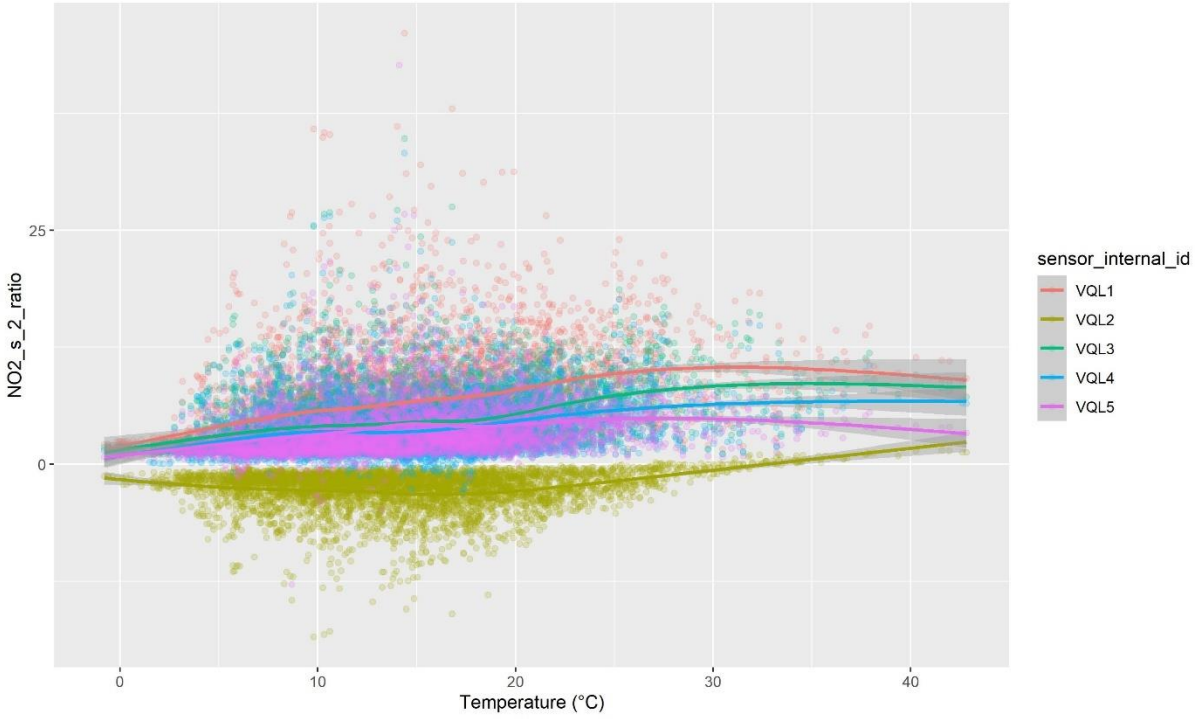


Figure 88: Membrapor C20 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to temperature (°C)

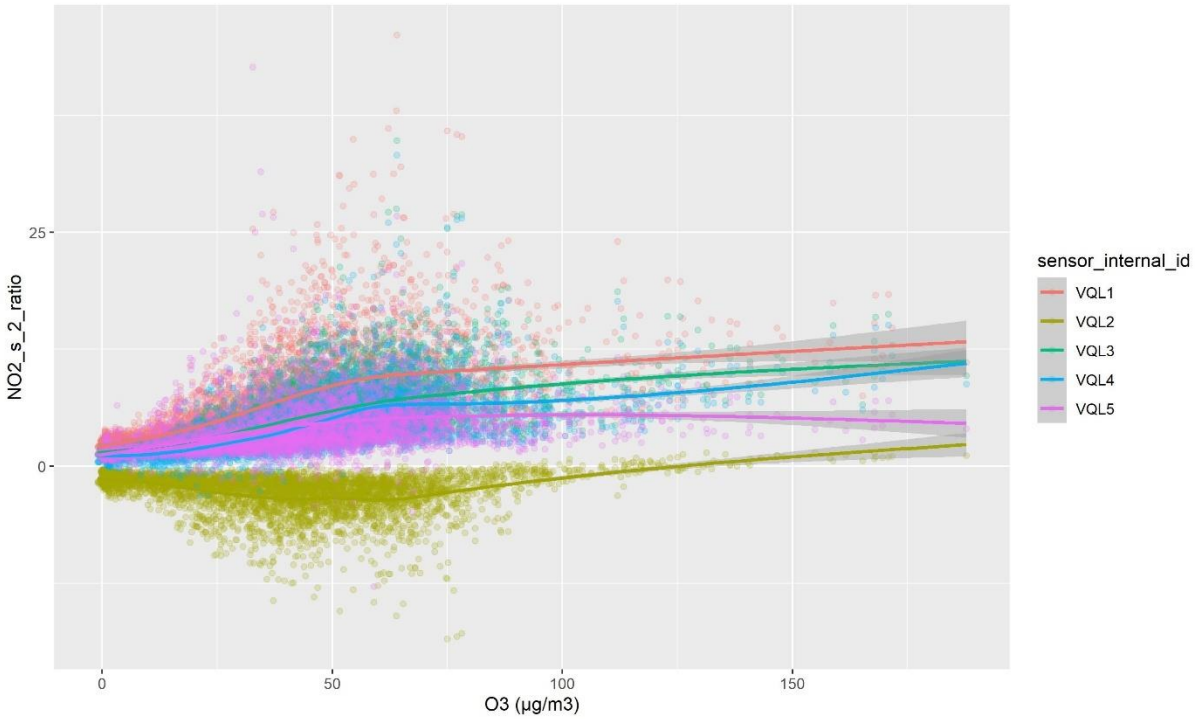


Figure 89: Membrapor C20 NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to O_3 ($\mu g/m^3$)

6.2.4 Descriptive parameters

Table 36: Membrapor C20 NO_2 sensor: Descriptive parameters for uncalibrated sensors. ID: sensor idea, n: number of values, R^2: coefficient of determination, Ubs: between sampler uncertainty

		Evaluation				
	ID	n	mean bias ($\mu g/m^3$)	R^2	u_{bs} ($\mu g/m^3$)	u_{bs} (%)
NO_2_s_2	VQL1	5405	105.06	0.01		
NO_2_s_2	VQL2	4891	-88.03	0.01		
NO_2_s_2	VQL3	5329	66.23	0.03		
NO_2_s_2	VQL4	5529	47.96	0.00		
NO_2_s_2	VQL5	5183	46.85	0.00		
NO_2_s_2	all sensors	26337			64.17	95.53

6.2.5 Relative expanded uncertainty

The calculation of the relative expanded uncertainty according to the Guidance of of Equivalence is based on the linear regression of the sensor data versus the reference data. As there is almost no correlation between the sensor data and the reference data, this calculation is not executed.

6.2.6 Conclusions

There is no or only very little correlation between the uncalibrated sensor data (*NO2_s_2*) and the reference data ($R^2 \leq 0.03$). The mean biases are very different for the individual sensors (between -88 and 105 µg/m^3).

As there is no or very little correlation between the sensor data and the reference data, a calibration with linear regression parameters based on the first month of field data is not executed.

6.3 Sensor data calibrated with parameters from multiple linear regression

6.3.1 Calibration parameters

The correlation chart (Appendix 1) shows no linear relation at all for sensor VQL5 between the uncalibrated sensor data (NO_2_s_2), relative humidity and temperature. This sensor is left out for further analysis.

Table 37: Membrapor C20 NO_2 sensor: Parameters from multiple linear regression (including NO2 reference measurements (NO2_ref), temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	T	RH
VQL1	121.9	0.09	1.26	0.04*
VQL2	-68.2	0.16	1.17	-0.24
VQL3	150.0	-0.01*	-1.06	-0.53
VQL4	123.0	-0.18	-0.93	-0.23

Table 38: Membrapor C20 NO_2 sensor: Parameters from extended multiple linear regression (including NO_2 reference measurements (NO2_ref), ozone reference measurements (O3_ref) temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	O_3_ref	T	RH
VQL1	-10.9	1.12	1.14	2.03	0.63
VQL2	-97.0	0.39	0.23	1.31	-0.09
VQL3	-5.5*	1.17	1.31	-0.22	0.20
VQL4	-63.9	1.22	1.58	0.19*	0.62

Variable not significant at 0.05 significance level

The correlation plots in annex 1 show relatively high correlation coefficients between the uncalibred sensor data *NO2_s_2* and reference O_3 (R between 0.60 and 0.67). Adding O_3 to the MRL indeed significantly improves the calibrated sensor data. In fact, there is almost no correlation ($R^2 \leq 0.05$) between the reference data and the sensor data calibrated with the MLR parameters without O_3 and therefore we will not discuss these calibrated sensor data *NO2_s_1mMLR2* any further.

6.3.2 Comparison sensor versus reference

6.3.2.1 Time plot and scatter plots of hourly values

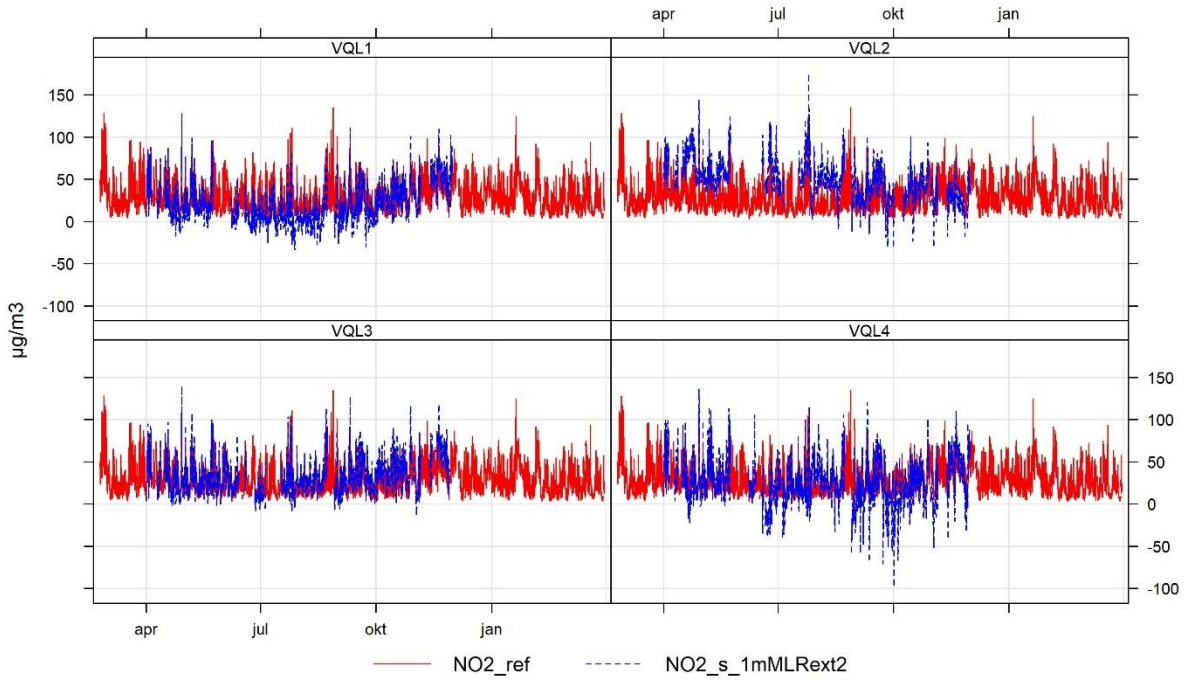


Figure 90: Membrapor C20 NO_2 sensor: Time plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

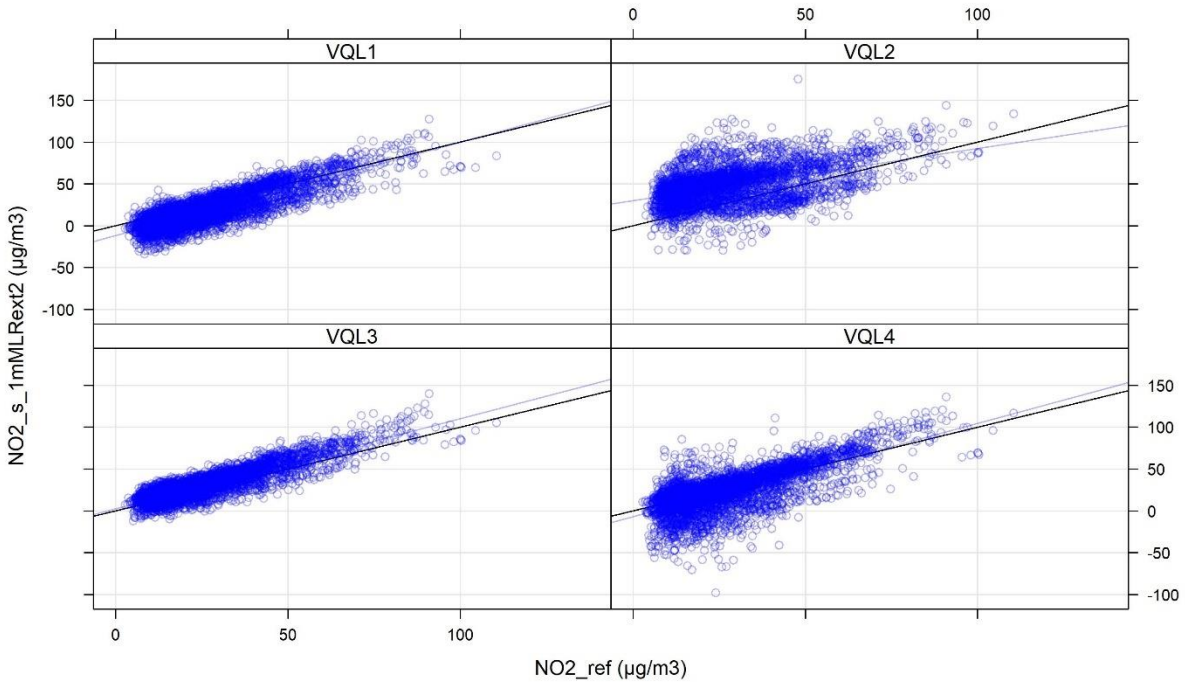


Figure 91: Membrapor C20 NO_2 sensor: Scatter plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

6.3.2.2 Ratio of hourly sensor values versus reference values

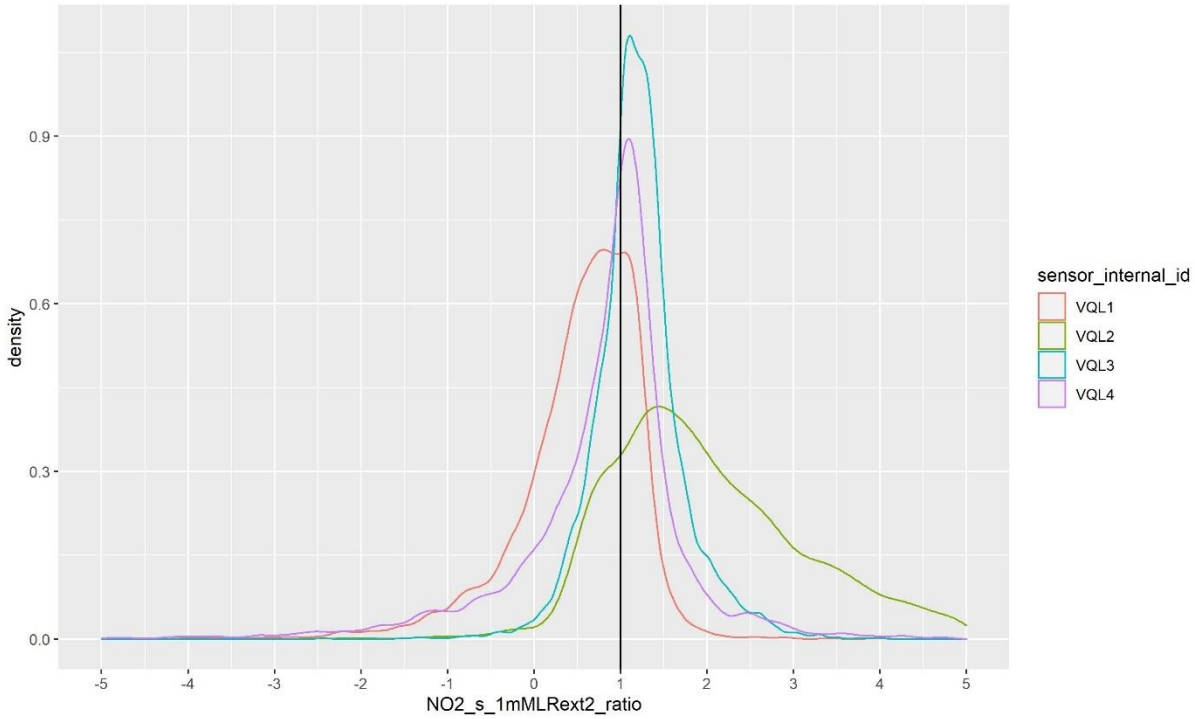


Figure 92: Membrapor C20 NO_2 sensor: Density plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values

6.3.3 Influence of time, temperature, relative humidity and O_3

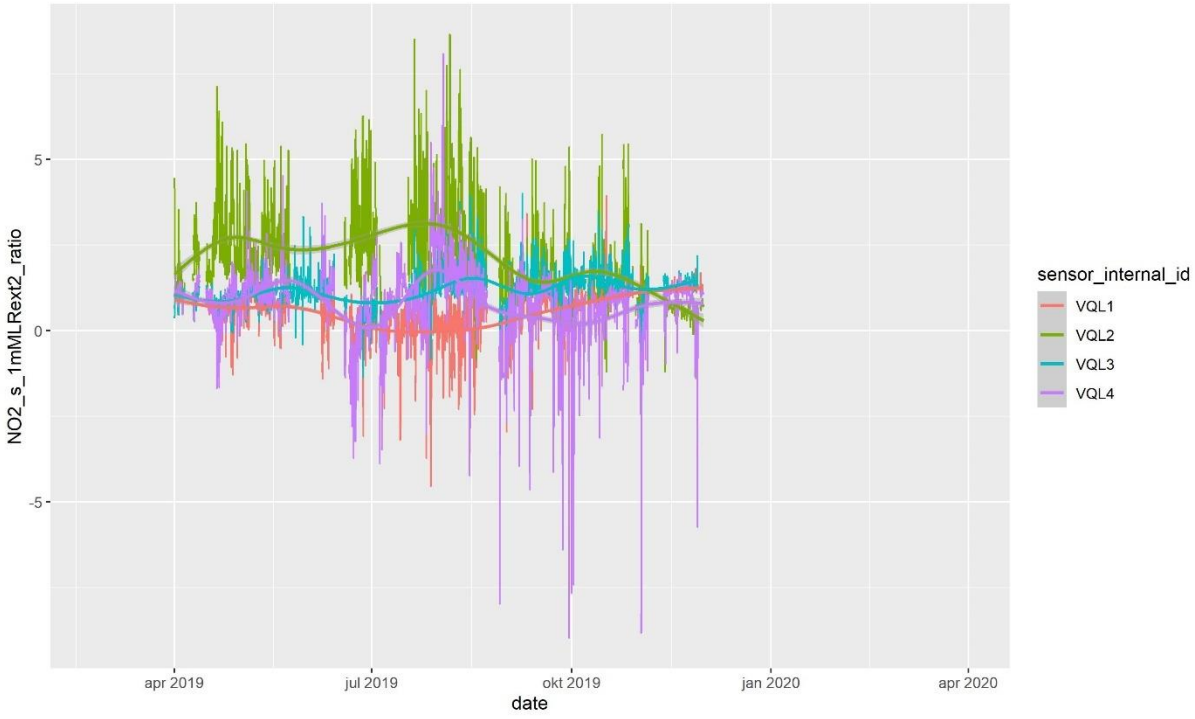


Figure 93: Membrapor C20 NO_2 sensor: Time plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values (µg/m³)

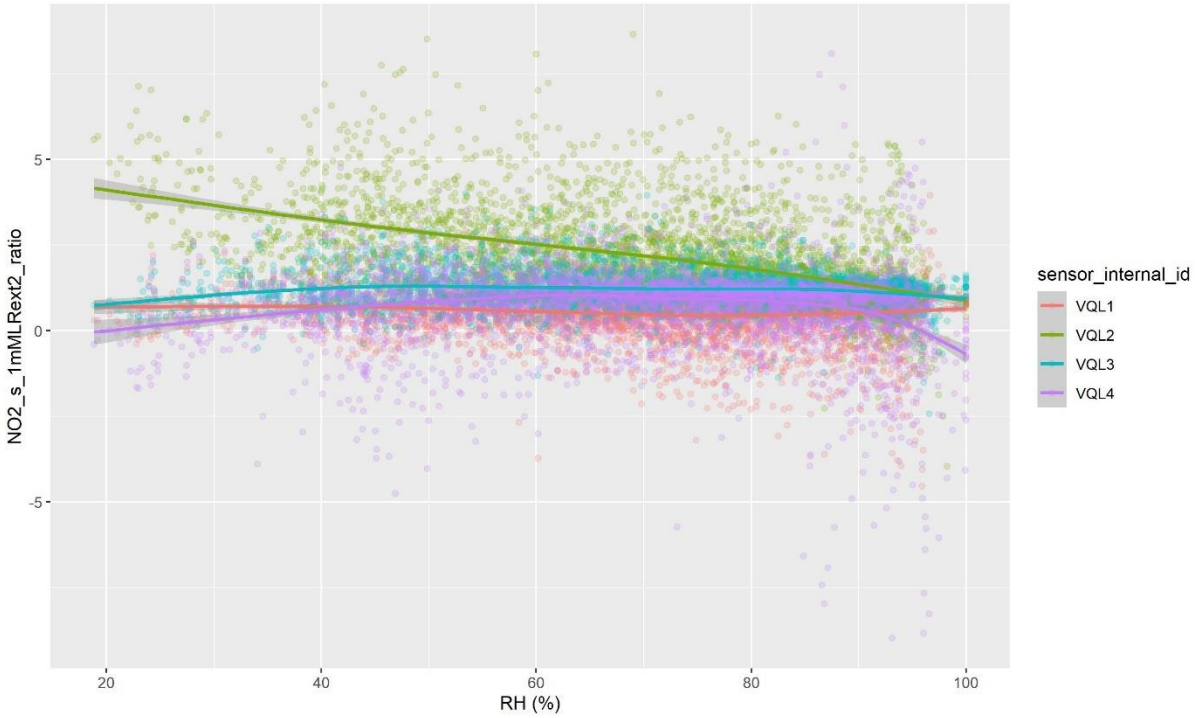


Figure 94: Membrapor C20 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to relative humidity (%)

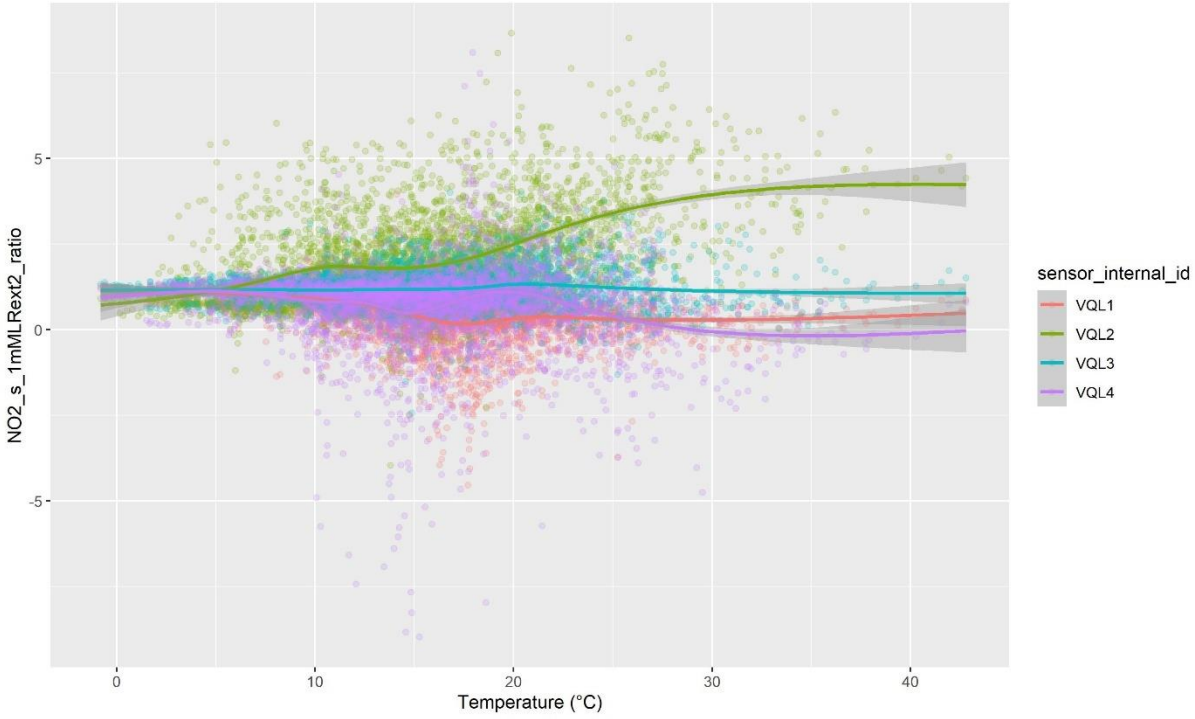


Figure 95: Membrapor C20 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to temperature (°C)

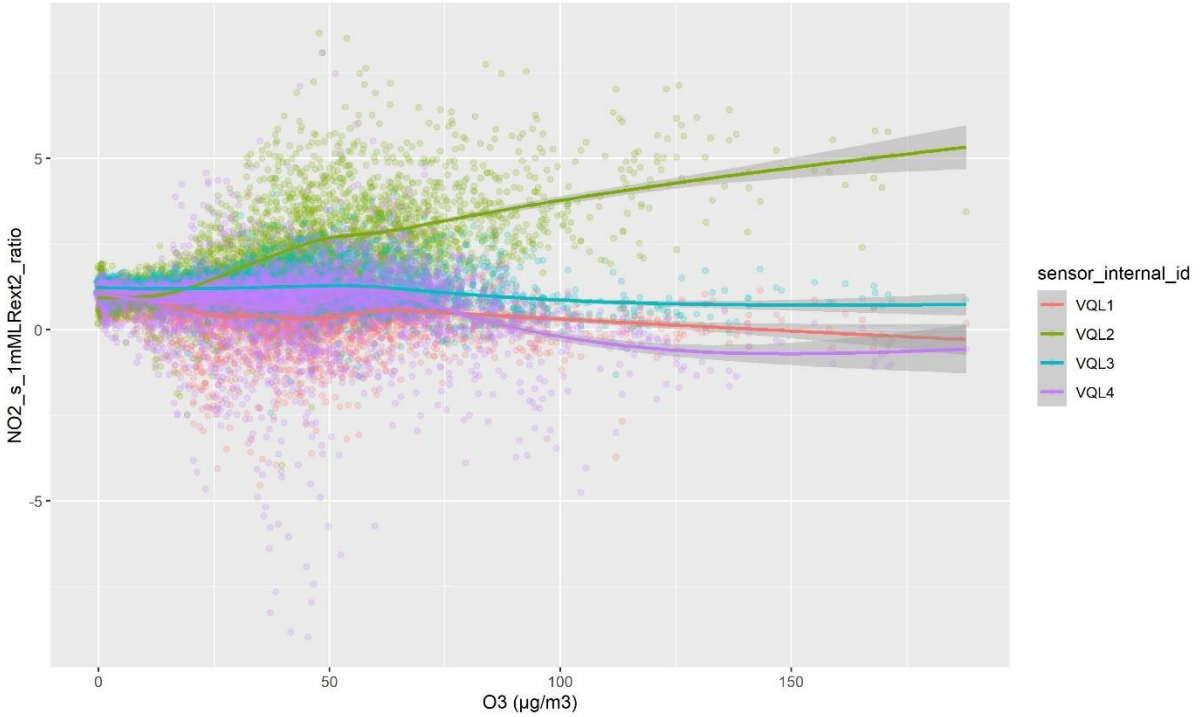


Figure 96: Membrapor C20 NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to ozone (µg/m³)

6.3.4 Descriptive parameters

Table 39: Membrapor C20 NO_2 sensor: Descriptive parameters for sensors calibrated with multiple linear regression and extended multiple linear regression. ID: sensor idea, n: number of values, R^2: coefficient of determination, Ubs: between sampler uncertainty

		Calibration		Evaluation				
	ID	n	R^2	n	mean bias ($\mu g/m^3$)	R^2	u_{bs} ($\mu g/m^3$)	u_{bs} (%)
NO_2_s_1mMLR2	VQL1	846	0.02	4536	-153.42	0.05		
NO_2_s_1mMLR2	VQL2	846	0.35	4028	44.43	0.01		
NO_2_s_1mMLR2	VQL3	845	0.00	4462	96.20	0.02		
NO_2_s_1mMLR2	VQL4	838	0.04	4667	68.36	0.00		
NO_2_s_1mMLR2	all			17693			981.68	2239.21
NO_2_s_1mMLRext2	VQL1	737	0.80	4419	-8.44	0.71		
NO_2_s_1mMLRext2	VQL2	737	0.82	3798	19.38	0.21		
NO_2_s_1mMLRext2	VQL3	736	0.92	4221	4.32	0.78		
NO_2_s_1mMLRext2	VQL4	729	0.79	4420	-3.92	0.52		
NO_2_s_1mMLRext2	all			16858			20.61	68.49

6.3.5 Relative expanded uncertainty

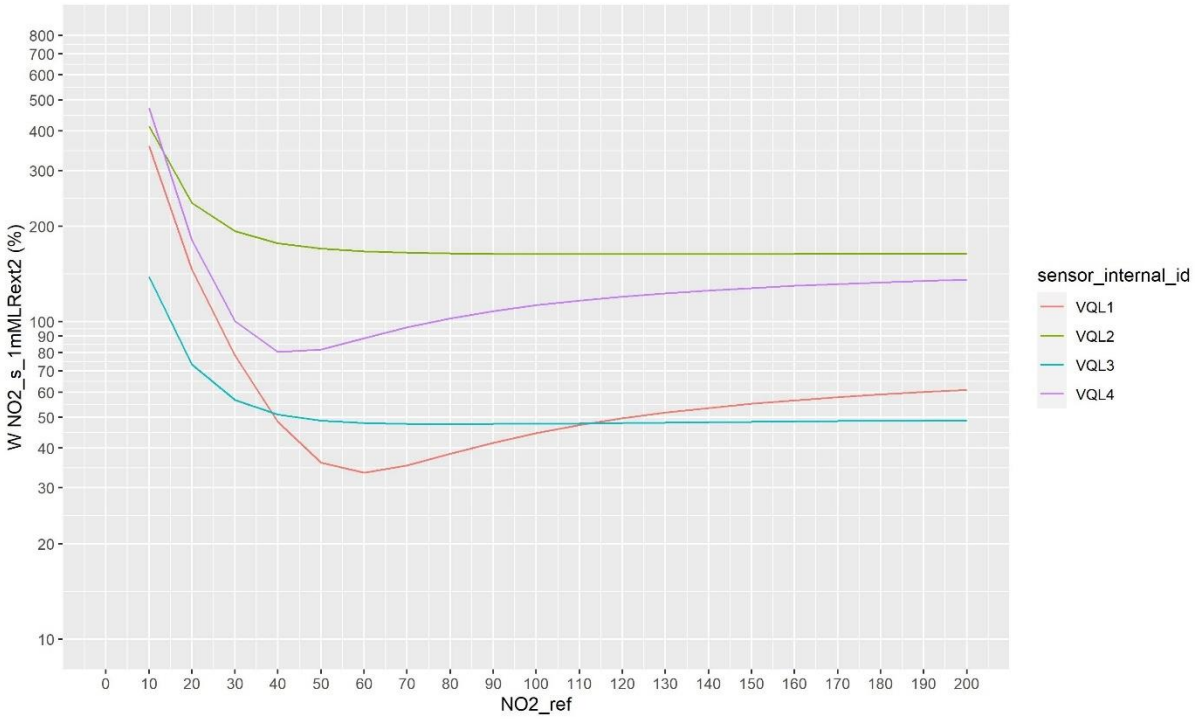


Figure 97: Membrapor C20 NO_2 sensor: Relative expanded uncertainty (W (%)) of sensor calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logarithmic scale

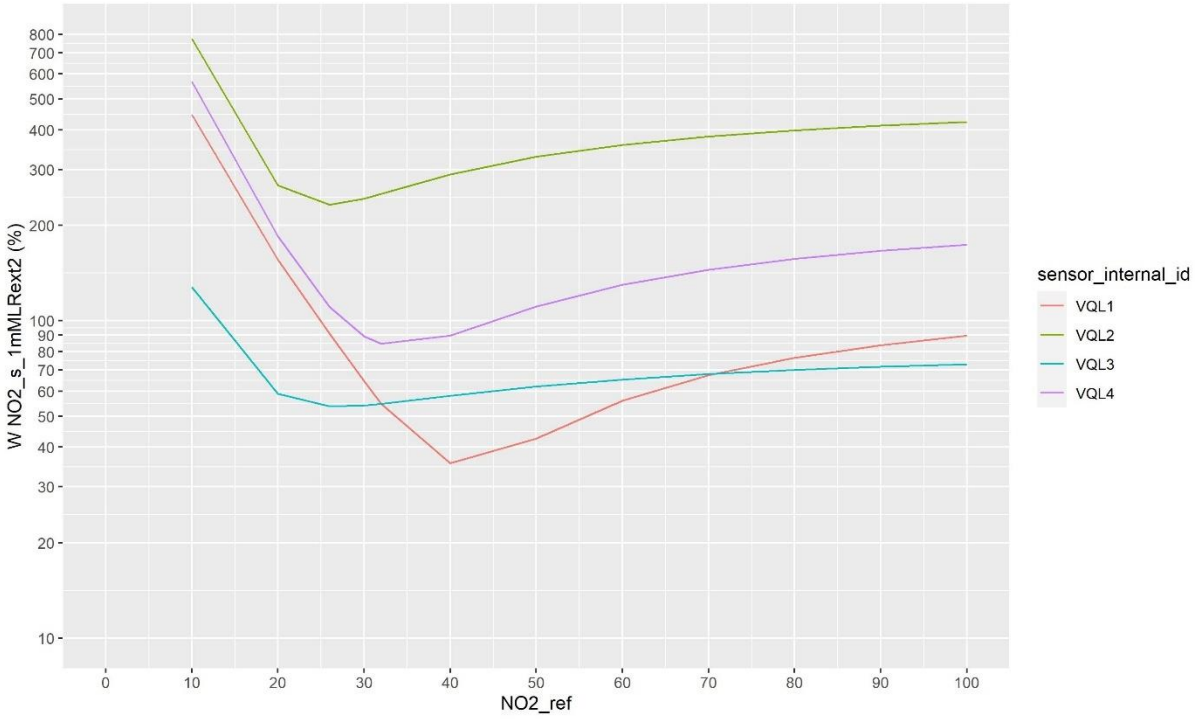


Figure 98: Membrapor C20 NO_2 sensor: Relative expanded uncertainty (W (%)) of sensors calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logaritmic scale.

Table 40: Membrapor C20 NO_2 sensor: Relative expanded uncertainty of sensors calibrated with extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO_2 hourly reference concentrations of 100 µg/m³ (LAT), 140 µg/m³ (UAT) and 200 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLRext2	VQL1	100.00	9.00	20.41	44.62
NO_2_s_1mMLRext2	VQL2	100.00	20.32	79.16	163.46
NO_2_s_1mMLRext2	VQL3	100.00	6.93	22.85	47.76
NO_2_s_1mMLRext2	VQL4	100.00	14.92	54.38	112.77
NO_2_s_1mMLRext2	VQL1	140.00	9.00	36.38	53.54
NO_2_s_1mMLRext2	VQL2	140.00	20.32	112.61	163.48
NO_2_s_1mMLRext2	VQL3	140.00	6.93	33.09	48.29
NO_2_s_1mMLRext2	VQL4	140.00	14.92	86.68	125.64
NO_2_s_1mMLRext2	VQL1	200.00	9.00	60.34	61.01
NO_2_s_1mMLRext2	VQL2	200.00	20.32	162.79	164.05
NO_2_s_1mMLRext2	VQL3	200.00	6.93	48.44	48.93
NO_2_s_1mMLRext2	VQL4	200.00	14.92	135.12	135.94

Table 41: Membrapor C20 NO_2 sensor: Relative expanded uncertainty of sensors calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO2 daily reference concentrations of 26 µg/m³ (LAT), 32 µg/m³ (UAT) and 40 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLRext2	VQL1	26	7.09	-9.51	91.20
NO_2_s_1mMLRext2	VQL2	26	26.65	14.21	232.28
NO_2_s_1mMLRext2	VQL3	26	5.70	4.04	53.75
NO_2_s_1mMLRext2	VQL4	26	13.38	-5.31	110.73
NO_2_s_1mMLRext2	VQL1	32	7.09	-5.14	54.72
NO_2_s_1mMLRext2	VQL2	32	26.65	30.11	251.28
NO_2_s_1mMLRext2	VQL3	32	5.70	6.63	54.68
NO_2_s_1mMLRext2	VQL4	32	13.38	2.09	84.66
NO_2_s_1mMLRext2	VQL1	40	7.09	0.68	35.59
NO_2_s_1mMLRext2	VQL2	40	26.65	51.30	289.06
NO_2_s_1mMLRext2	VQL3	40	5.70	10.10	57.99
NO_2_s_1mMLRext2	VQL4	40	13.38	11.96	89.74

Table 42: Membrapor C20 NO_2 sensor: Parameters of orthogonal regression of hourly and daily sensor data calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) versus reference NO2

		hourly values		daily values	
	ID	slope	intercept (µg/m³)	slope	intercept (µg/m³)
NO_2_s_1mMLRext2	VQL1	1.40	-19.51	1.73	-28.41
NO_2_s_1mMLRext2	VQL2	1.84	-4.46	3.65	-54.69
NO_2_s_1mMLRext2	VQL3	1.26	-2.73	1.43	-7.22
NO_2_s_1mMLRext2	VQL4	1.81	-26.36	2.23	-37.37

6.3.6 Conclusions

There is almost no correlation ($R^2 \leq 0.05$) between the reference data and the sensor data calibrated with the parameters from MLR without O_3 (*NO2_s_1mMLR2*). Adding O_3 to the MRL is necessary to obtain correlation between the reference data and the calibrated sensor data (*NO2_s_1mMLRext2*).

Overall we see less scatter in the ratios of the sensor data *NO2_s_1mMLRext2* versus reference data in function of time, temperature, relative humidity and O_3 in comparison to the sensor data *NO2_s_1m2.*

The R^2 is 0.78 for sensor VQL3, 0.71 for sensor VQL1, 0.52 for sensor VQL4 but only 0.21 for sensor VQL2. This sensor was excluded from the data analysis of the lab test due to diverging behavior. The mean biases vary between -8 and 20 µg/m^3. The between sensor uncertainty is 68 %.

VQL1 and VQL3 are the only sensors for which the expanded uncertainty for the hourly data is ≤ 75 % at the LV (200 µg/m^3), the UAT (140 µg/m^3) and the LAT (100 µg/m^3).

The expanded uncertainty of the daily sensor data is also ≤ 75 % at the LV (40 µg/m^3) and the UAT (32 µg/m^3) for these two sensors. For VQL3 the expanded uncertainty is also ≤ 75 % at the LAT (26 µg/m^3).

The expanded uncertainty at the LV, the UAT and LAT for the hourly and daily sensor data *NO2_s_1mMLRext2* is always > 25 %.

Field Evaluation
Envea Cairclip NO_2 sensor

Manufacturer: Envea

Link to website manufacturer

Link to test protocol

7 Envea Cairclip NO_2 sensor

7.1 Validation and data coverage

The time resolution configured for these sensors was fifteen minutes. The sensors don't give negative values.

These sensors needed to be read out manually. Data were marked as invalid on the moments when the data were read out. Very few data were marked suspicious. VQS2 and VQS3 lost their time indication in June and VQS1 and VQS4 in August. After reconfiguration the sensors gave the indication that the lifetime was exceeded. The lifetime of this sensor type is one year.

VQS4 was tested in the laboratory, but diverging from the other sensors and was therefore not included in the evaluation of the laboratory testing.

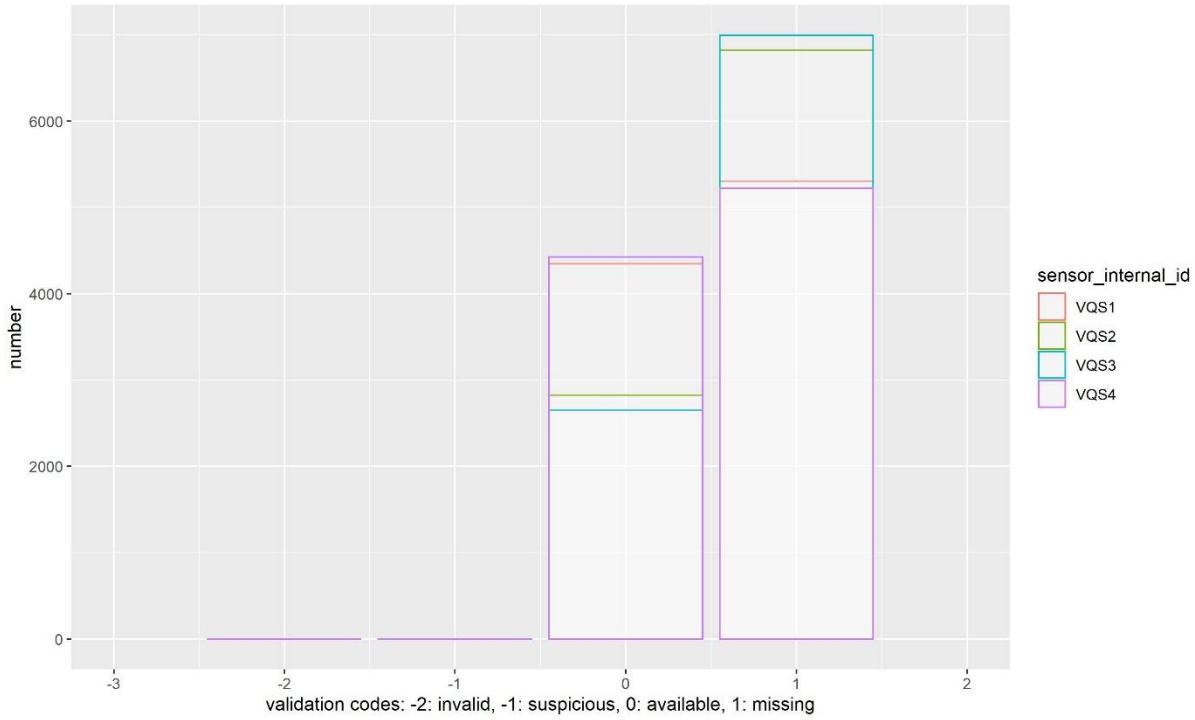


Figure 99: Envea Cairclip NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing)

Table 43: Envea Cairclip NO_2 sensor: Number sensor hourly values (-2: invalid, -1: suspicious, 0: valid, 1: missing) and percentage of available data

	-2	-1	0	1	% available
VQS1	0	1	4345	5302	45
VQS2	0	0	2825	6823	29
VQS3	0	0	2654	6994	27
VQS4	0	1	4428	5219	46

7.2 Uncalibrated sensor data and sensor data calibrated with parameters from linear regression

7.2.1 Calibration parameters

Table 44: Envea Cairclip NO_2 sensor: Parameters from linear regression against reference method - hourly field data from February 23 2019 - March 31 2019

sensor_internal_id	slope	intercept
VQS1	0.21	-2.96
VQS2	0.43	-3.49
VQS3	0.27	-5.02
VQS4	0.23	-0.76

7.2.2 Comparison sensor versus reference

7.2.2.1 Time plot and scatter plots of hourly values

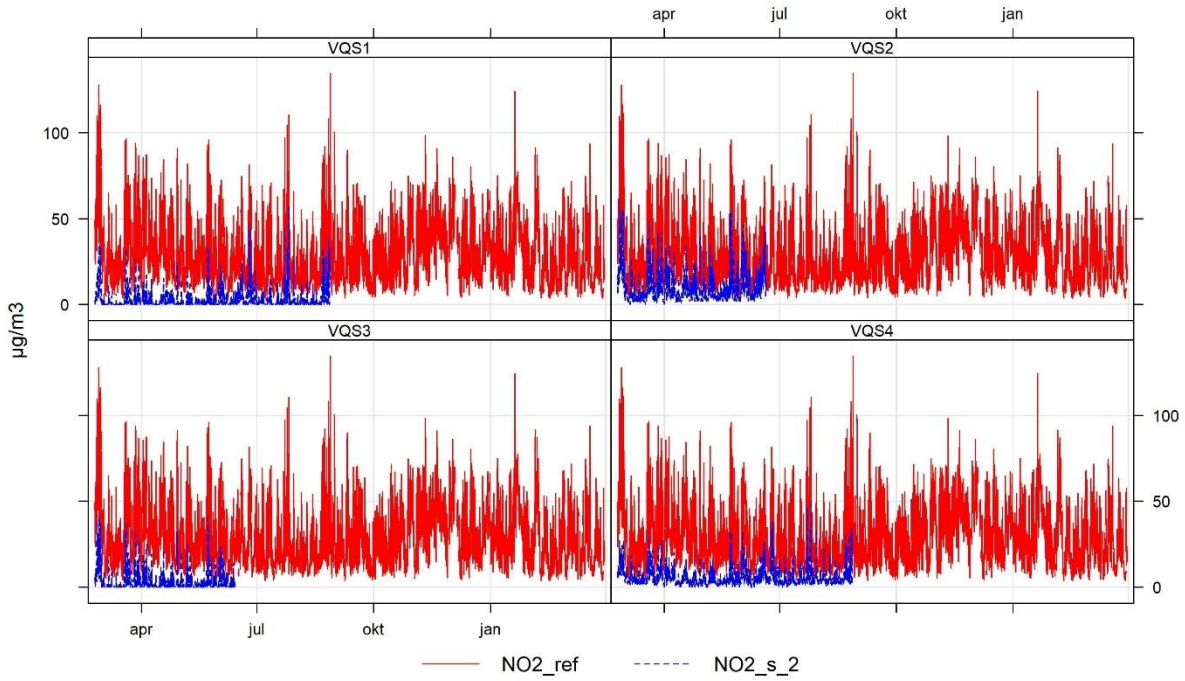


Figure 100: Envea Cairclip NO_2 sensor: Time plot uncalibrated sensor hourly values and reference values (µg/m³)

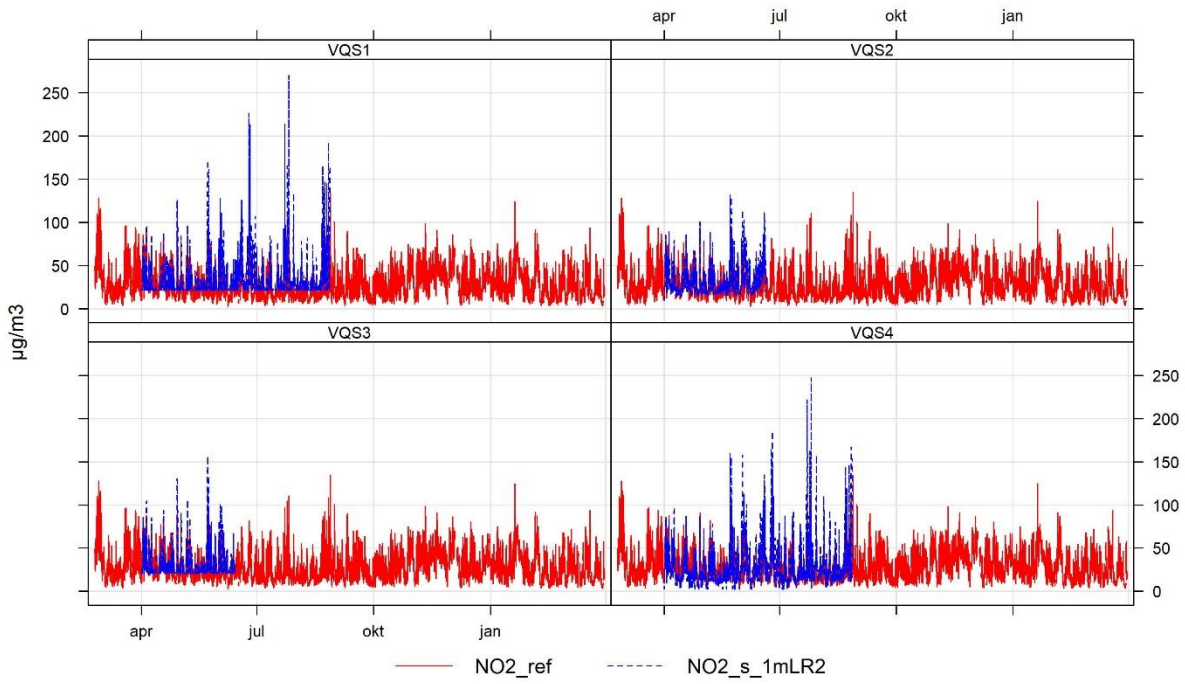


Figure 101: Envea Cairclip NO_2 sensor: Time plot of sensor hourly values calibrated with the linear regression parameters and reference values (µg/m³)

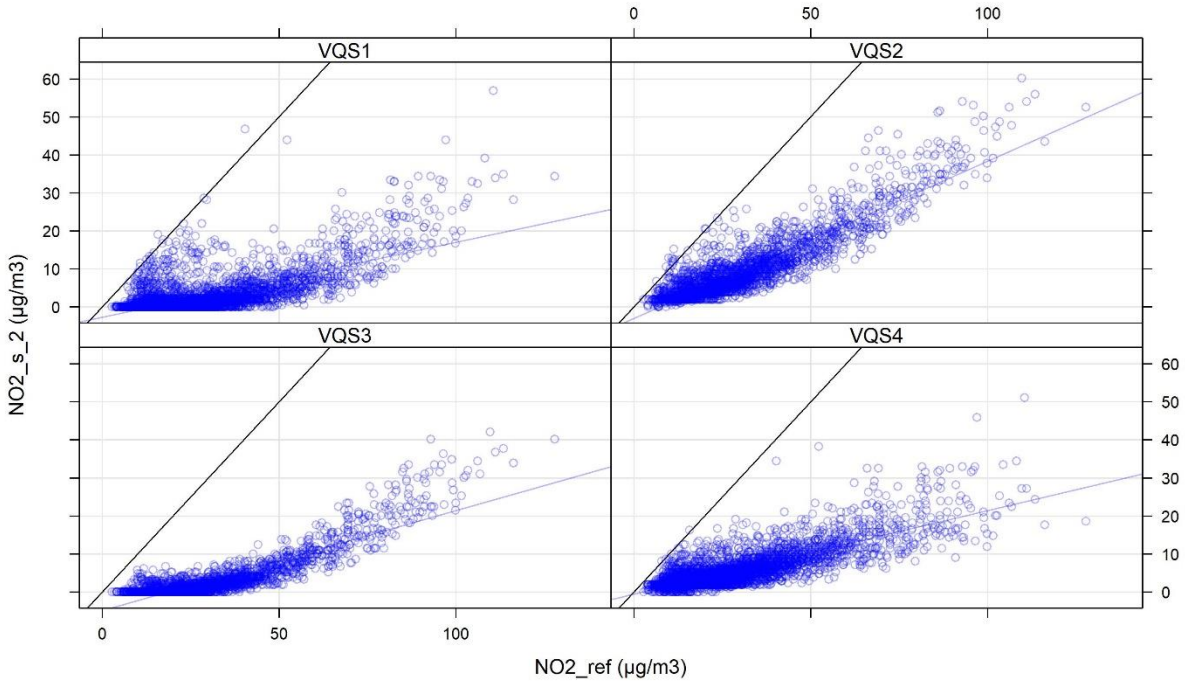


Figure 102: Envea Cairclip NO_2 sensor: Scatter plot of uncalibrated sensor hourly values versus reference values (µg/m³)

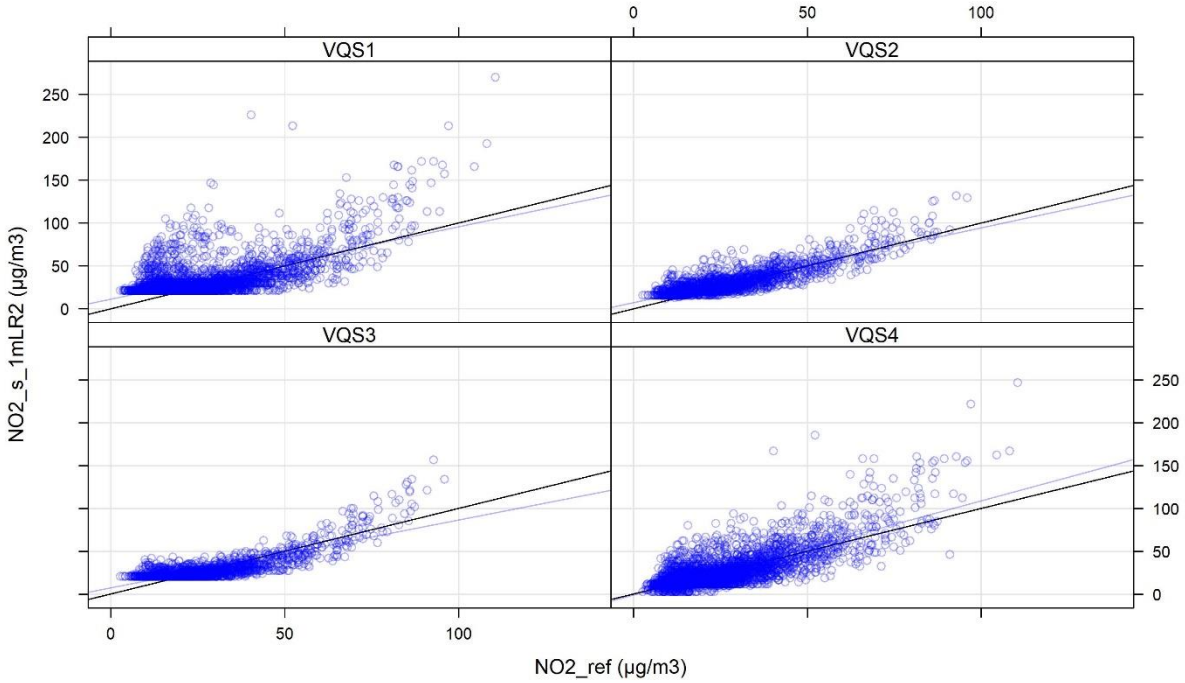


Figure 103: Envea Cairclip NO_2 sensor: Scatter plot sensor hourly values calibrated with the linear regression parameters versus reference values (µg/m³)

7.2.2.2 Ratio of hourly sensor values versus reference values

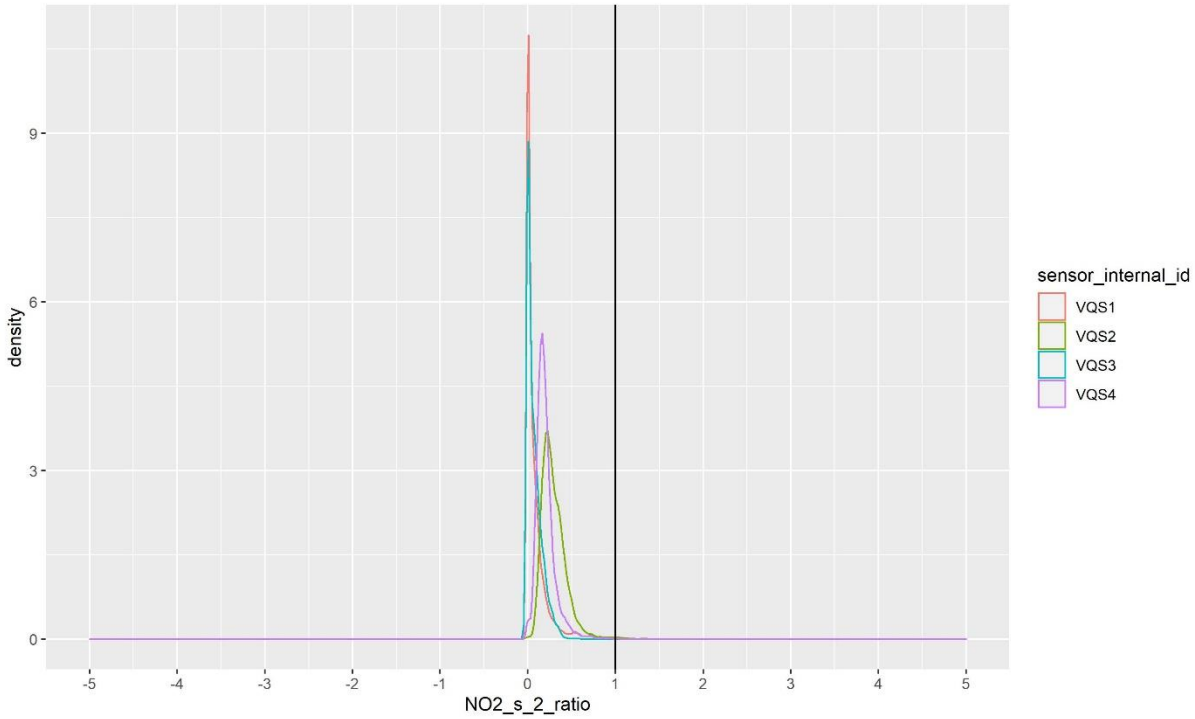


Figure 104: Envea Cairclip NO_2 sensor: Density plot of uncalibrated ratio sensor hourly values versus reference values

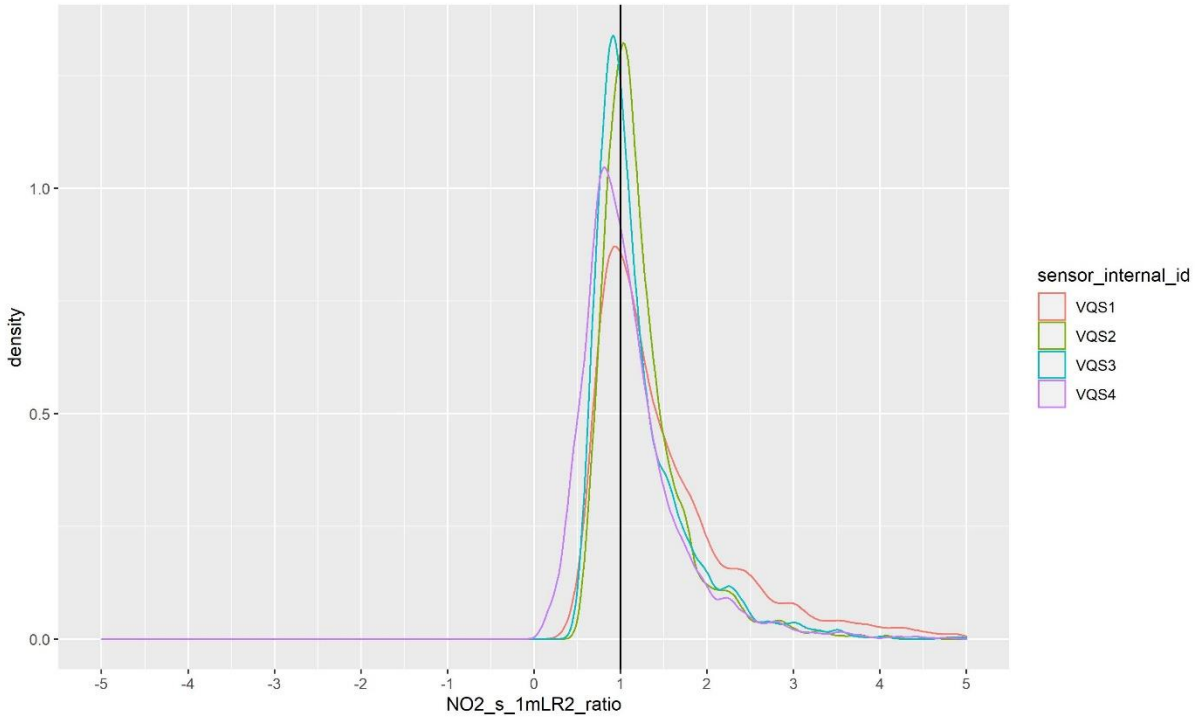


Figure 105: Envea Cairclip NO_2 sensor: Density plot of ratio sensor hourly values calibrated with the linear regression parameters versus reference values

7.2.3 Influence of time, temperature, relative humidity and O_3

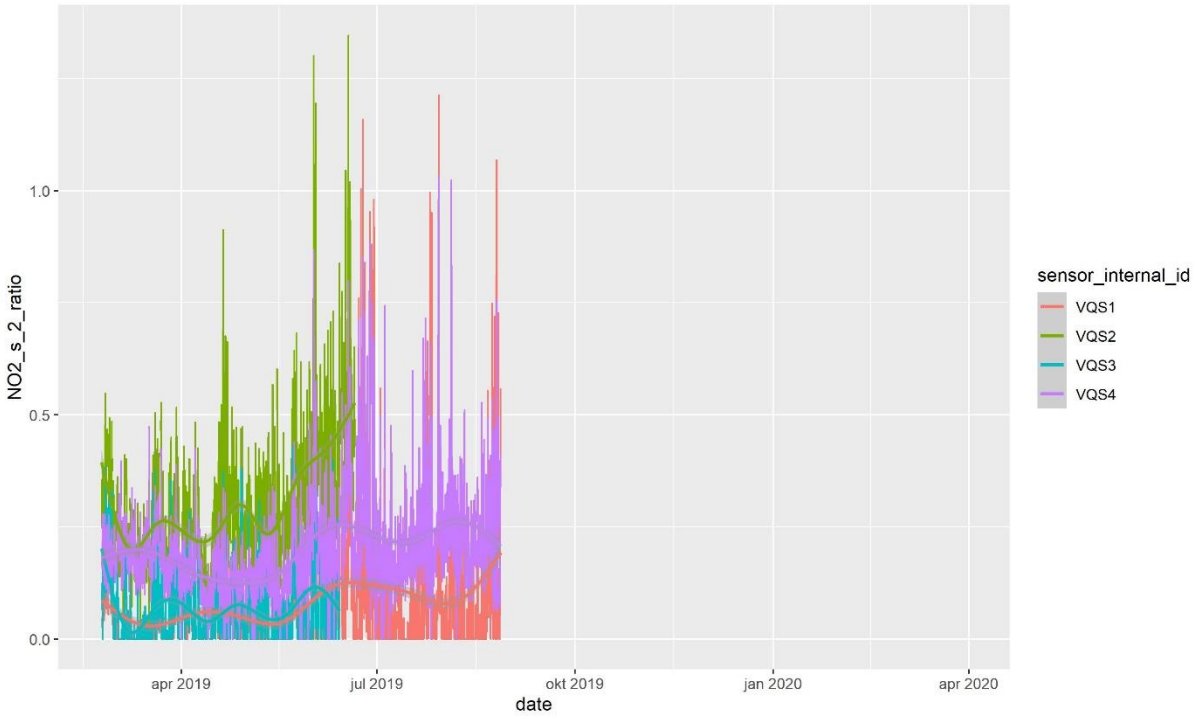


Figure 106: Envea Cairclip NO_2 sensor: Time plot ratio sensor hourly values versus reference values (µg/m³)

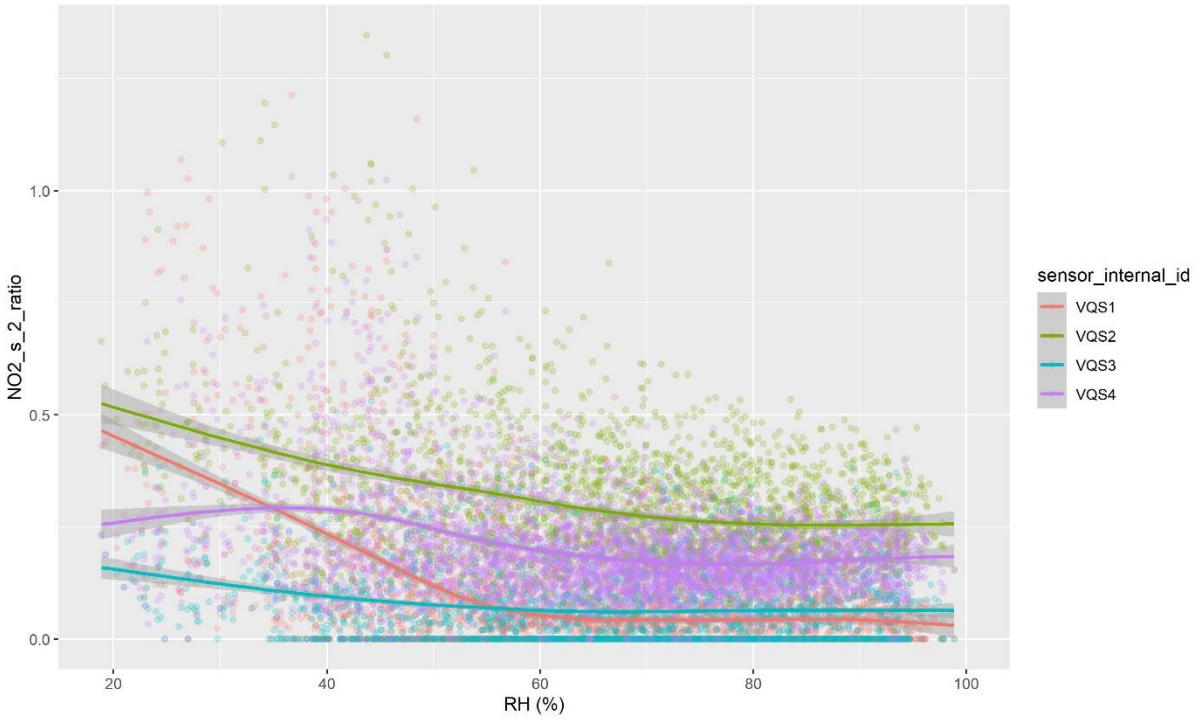


Figure 107: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to relative humidity (%)

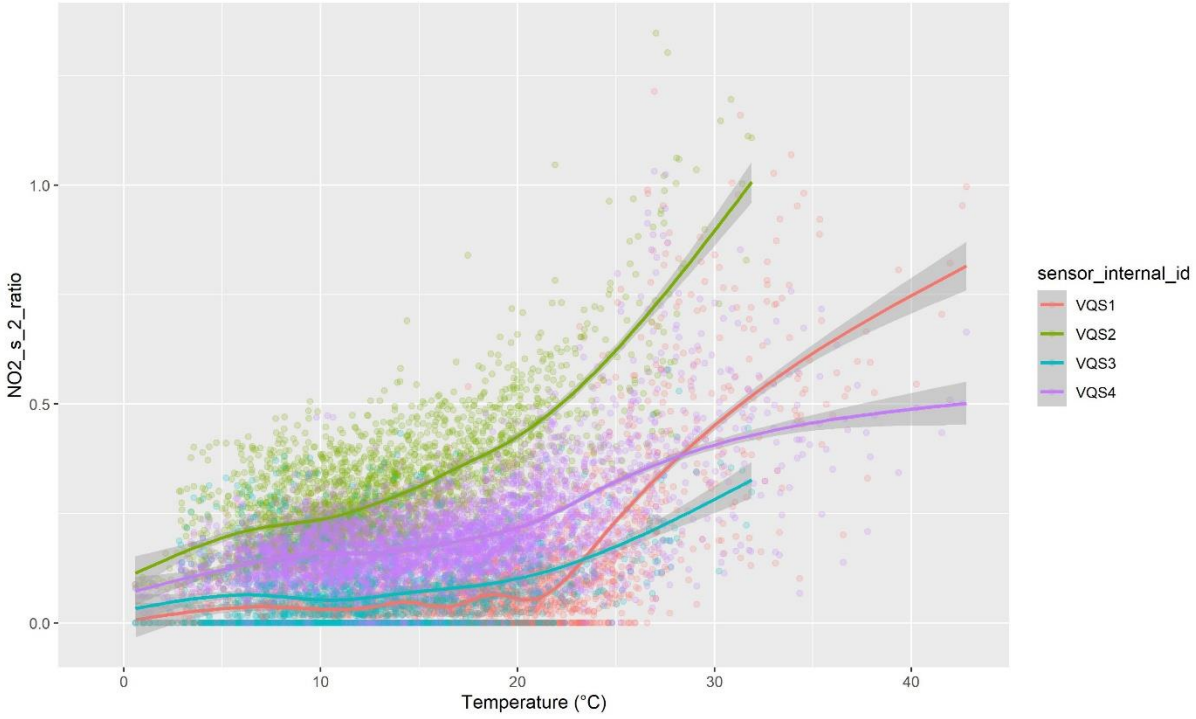


Figure 108: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to temperature (°C)

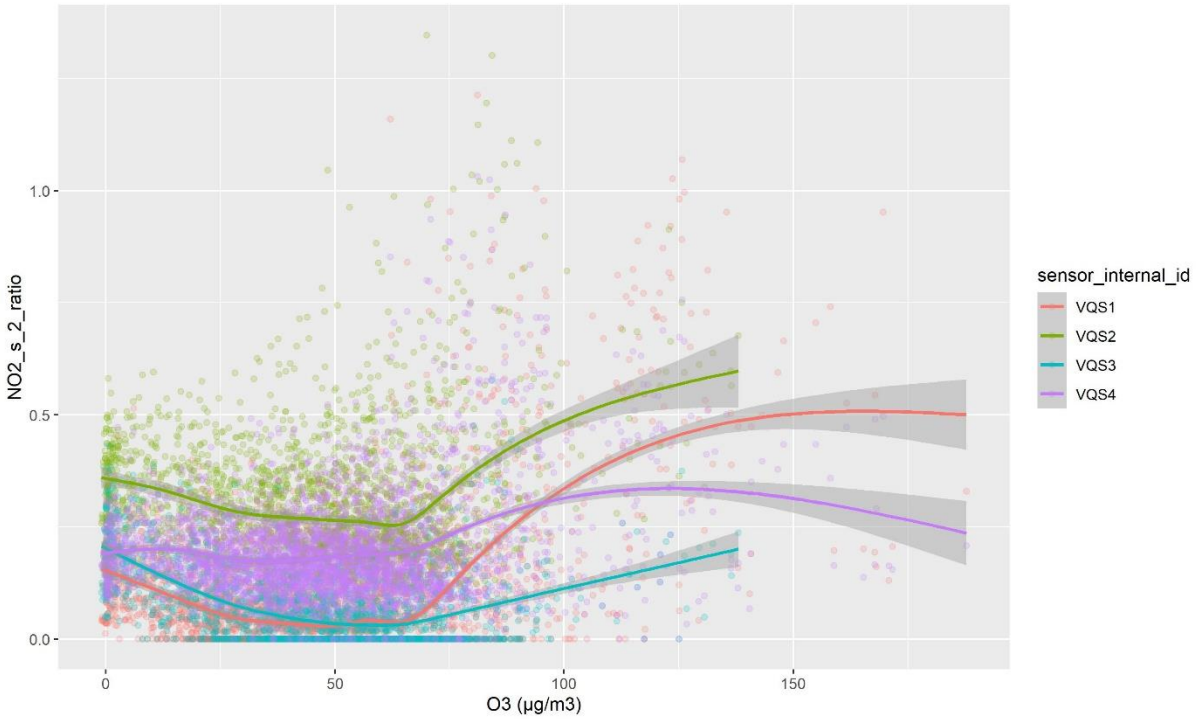


Figure 109: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values versus reference values in relation to O_3 ($\mu g/m^3$)

7.2.4 Descriptive parameters

Table 45: Envea Cairclip NO_2 sensor: Descriptive parameters for uncalibrated sensors (NO2_S_2) and sensors calibrated with the linear regression parameters (NO2_S_1mLR2). ID: sensor idea, n: number of values, R^2: coefficient of determination, Ubs: between sampler uncertainty

		Calibration		Evaluation				
	ID	n	R^2	n	mean bias ($\mu g/m^3$)	R^2	u_{bs} ($\mu g/m^3$)	u_{bs} (%)
NO_2_s_2	VQS1			4070	-24.91	0.48		
NO_2_s_2	VQS2			2623	-21.20	0.82		
NO_2_s_2	VQS3			2491	-27.71	0.77		
NO_2_s_2	VQS4			4150	-22.42	0.66		
NO_2_s_2	all sensors			13334			5.18	101.94
NO_2_s_1mLR2	VQS1	768	0.77	3302	7.01	0.40		
NO_2_s_1mLR2	VQS2	846	0.93	1777	3.43	0.71		
NO_2_s_1mLR2	VQS3	846	0.86	1645	1.33	0.67		
NO_2_s_1mLR2	VQS4	826	0.82	3324	1.53	0.60		
NO_2_s_1mLR2	all sensors			10048			17.41	56.98

7.2.5 Relative expanded uncertainty

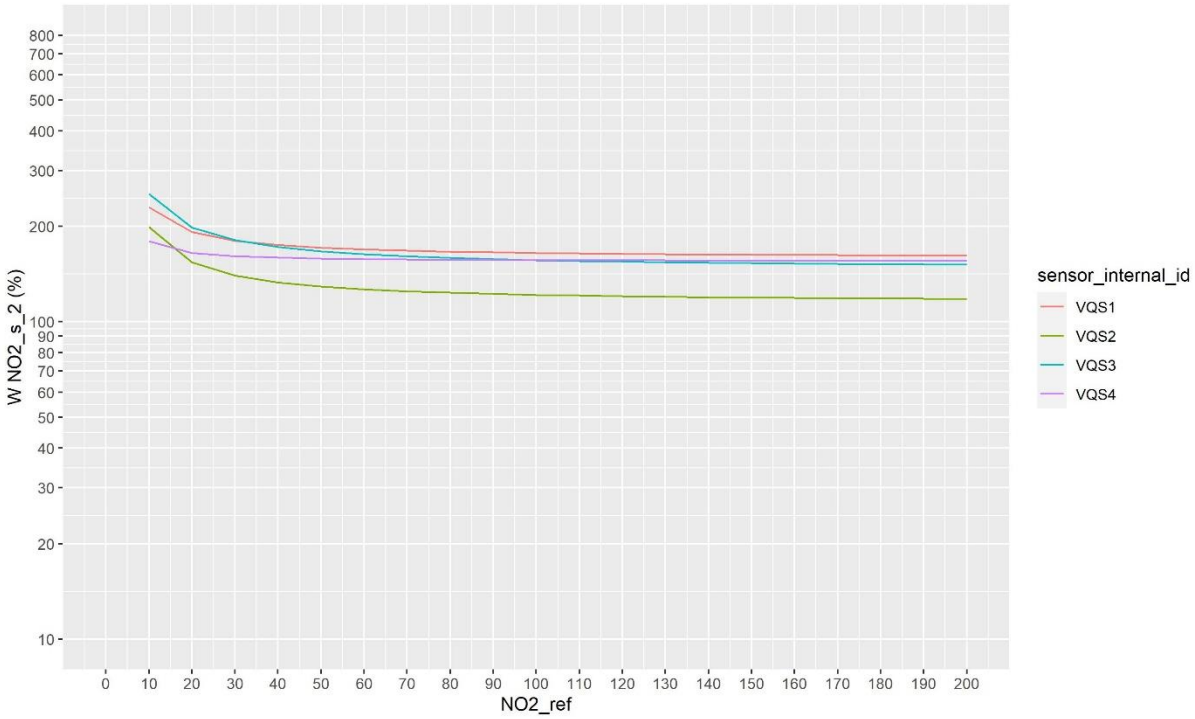


Figure 110: Envea Cairclip NO_2 sensor: Relative expanded uncertainty (W (%)) for uncalibrated sensor values according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³

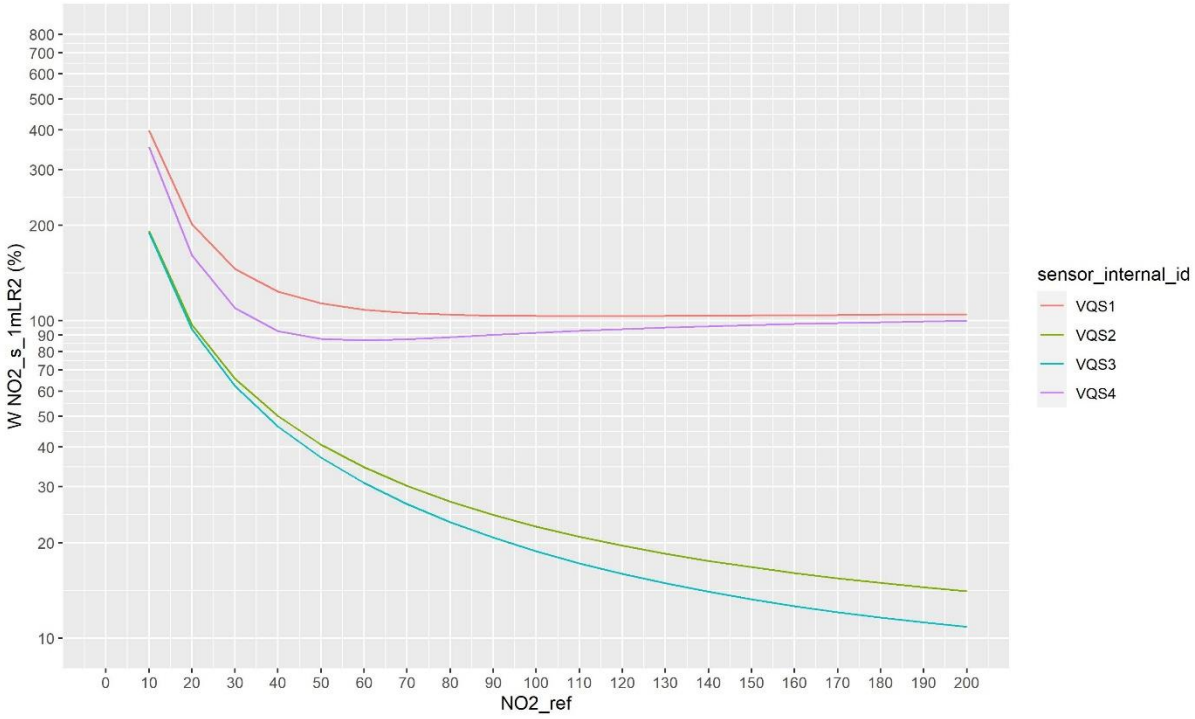


Figure 111: Envea Cairclip NO_2 sensor: Relative expanded uncertainty (W (%)) for sensor values calibrated with the linear regression parameters according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³

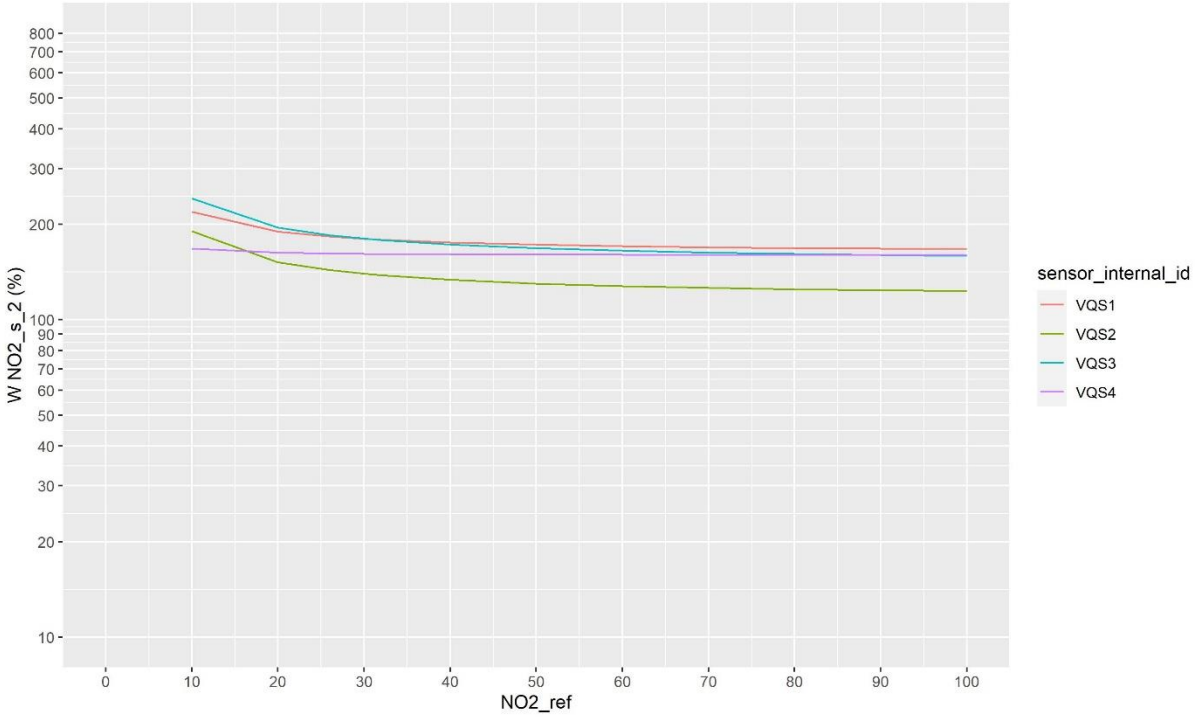


Figure 112: Envea Cairclip NO_2 sensor: Relative expanded uncertainty (W (%)) for uncalibrated sensor values according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³

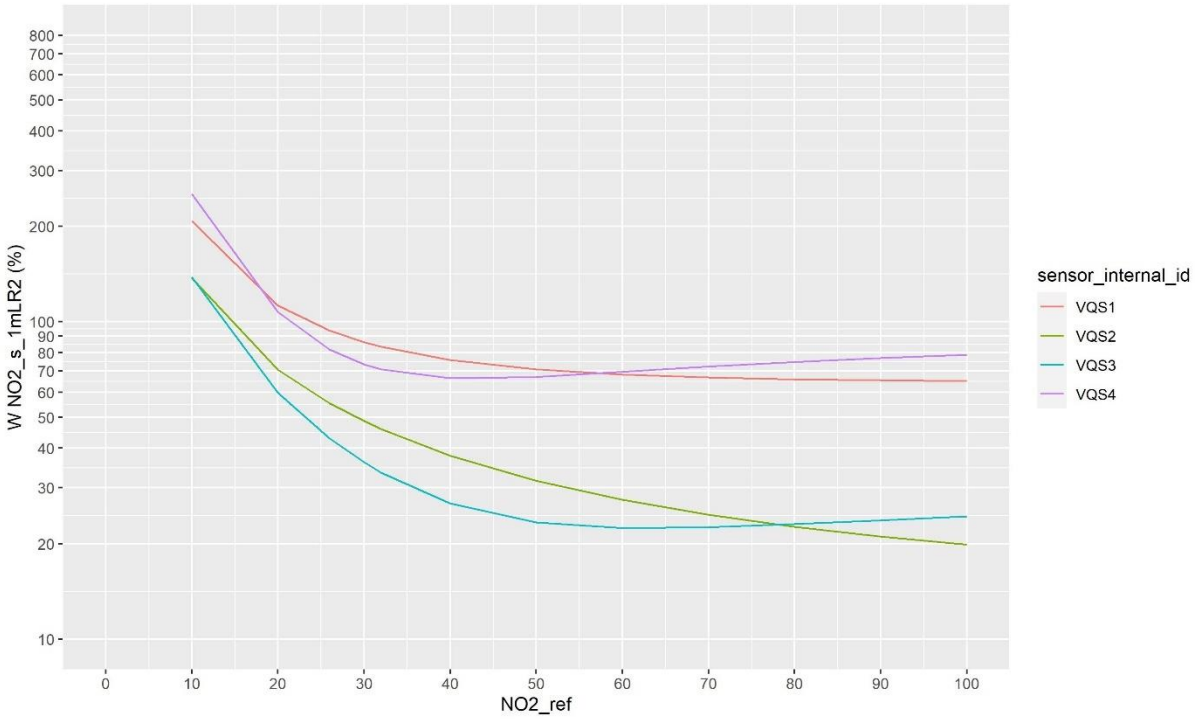


Figure 113: Envea Cairclip NO_2 sensor: Relative expanded uncertainty (W (%)) for sensor values calibrated with the linear regression parameters according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³

Table 46: Envea Cairclip NO_2 sensor: Relative expanded uncertainty for uncalibrated sensors (NO2_S_2) and for sensors calibrated with the linear regression parameters (NO2_S_1mLR2) according to Guidance of Equivalence calculated at NO2 hourly reference concentrations of 100 µg/m³ (LAT), 140 µg/m³ (UAT) and 200 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_2	VQS1	100	3.63	-82.37	164.90
NO_2_s_2	VQS2	100	3.72	-60.72	121.66
NO_2_s_2	VQS3	100	2.72	-78.21	156.51
NO_2_s_2	VQS4	100	2.86	-78.23	156.57
NO_2_s_1mLR2	VQS1	100	19.85	47.83	103.57
NO_2_s_1mLR2	VQS2	100	9.22	6.42	22.47
NO_2_s_1mLR2	VQS3	100	9.26	-1.57	18.78
NO_2_s_1mLR2	VQS4	100	16.01	42.94	91.65
NO_2_s_2	VQS1	140	3.63	-114.13	163.13
NO_2_s_2	VQS2	140	3.72	-83.61	119.56
NO_2_s_2	VQS3	140	2.72	-107.48	153.60
NO_2_s_2	VQS4	140	2.86	-109.22	156.09
NO_2_s_1mLR2	VQS1	140	19.85	69.89	103.80
NO_2_s_1mLR2	VQS2	140	9.22	8.09	17.53
NO_2_s_1mLR2	VQS3	140	9.26	-3.20	13.99
NO_2_s_1mLR2	VQS4	140	16.01	65.33	96.09
NO_2_s_2	VQS1	200	3.63	-161.78	161.82
NO_2_s_2	VQS2	200	3.72	-117.94	118.00
NO_2_s_2	VQS3	200	2.72	-151.40	151.42
NO_2_s_2	VQS4	200	2.86	-155.71	155.73
NO_2_s_1mLR2	VQS1	200	19.85	102.99	104.88
NO_2_s_1mLR2	VQS2	200	9.22	10.60	14.05
NO_2_s_1mLR2	VQS3	200	9.26	-5.65	10.84
NO_2_s_1mLR2	VQS4	200	16.01	98.91	100.19

Table 47: Envea Cairclip NO_2 sensor: Relative expanded uncertainty for uncalibrated sensors (NO_2_S_2) and for sensors calibrated with the linear regression parameters (NO_2_S_1mLR2) according to Guidance of Equivalence calculated at NO2 daily reference concentrations of 26 µg/m³ (LAT), 32 µg/m³ (UAT) and 40 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_2	VQS1	26	1.96	-23.70	182.96
NO_2_s_2	VQS2	26	2.45	-18.49	143.44
NO_2_s_2	VQS3	26	1.44	-23.99	184.88
NO_2_s_2	VQS4	26	1.80	-20.95	161.75
NO_2_s_1mLR2	VQS1	26	10.30	6.54	93.83
NO_2_s_1mLR2	VQS2	26	6.61	2.84	55.32
NO_2_s_1mLR2	VQS3	26	5.32	1.70	42.92
NO_2_s_1mLR2	VQS4	26	10.58	1.06	81.79
NO_2_s_2	VQS1	32	1.96	-28.55	178.87
NO_2_s_2	VQS2	32	2.45	-21.97	138.19
NO_2_s_2	VQS3	32	1.44	-28.50	178.37
NO_2_s_2	VQS4	32	1.80	-25.73	161.23
NO_2_s_1mLR2	VQS1	32	10.30	8.51	83.49
NO_2_s_1mLR2	VQS2	32	6.61	3.21	45.91
NO_2_s_1mLR2	VQS3	32	5.32	0.67	33.48
NO_2_s_1mLR2	VQS4	32	10.58	4.05	70.81
NO_2_s_2	VQS1	40	1.96	-35.02	175.36
NO_2_s_2	VQS2	40	2.45	-26.63	133.70
NO_2_s_2	VQS3	40	1.44	-34.52	172.74
NO_2_s_2	VQS4	40	1.80	-32.11	160.81
NO_2_s_1mLR2	VQS1	40	10.30	11.14	75.84
NO_2_s_1mLR2	VQS2	40	6.61	3.70	37.87
NO_2_s_1mLR2	VQS3	40	5.32	-0.70	26.80
NO_2_s_1mLR2	VQS4	40	10.58	8.04	66.44

Table 48: Envea Cairclip NO_2 sensor: Parameters of orthogonal regression of hourly and daily sensor data versus reference NO_2 for uncalibrated sensors (NO2_S_2) and for sensors calibrated with the linear regression parameters (NO2_S_1mLR2)

		hourly values		daily values	
	ID	slope	intercept ($\mu g/m^3$)	slope	intercept ($\mu g/m^3$)
NO_2_s_2	VQS1	0.21	-2.96	0.19	-2.69
NO_2_s_2	VQS2	0.43	-3.49	0.42	-3.37
NO_2_s_2	VQS3	0.27	-5.02	0.25	-4.44
NO_2_s_2	VQS4	0.23	-0.76	0.20	-0.22
NO_2_s_1mLR2	VQS1	1.55	-7.32	1.33	-2.00
NO_2_s_1mLR2	VQS2	1.04	2.23	1.06	1.23
NO_2_s_1mLR2	VQS3	0.96	2.50	0.83	6.14
NO_2_s_1mLR2	VQS4	1.56	-13.03	1.50	-11.89

7.2.6 Conclusions

The plots with the ratios of the uncalibrated sensor data (*NO2_s_2*) and the reference data shows no occurrence of drift. We see an influence of temperature on the sensor data.

The sensors largely underestimate the NO_2 concentrations. The sensors sometimes give a zero signal for relative high NO_2 concentrations. This is most pronounced for the sensors VQS1 and VQS3.

The mean biases of the uncalibrated sensor data (*NO2_s_2*) versus the reference data are negative (between -28 and -21 µg/m^3) for all the sensors. The R^2 varies between 0.48 and 0.82.

Calibration of the sensors with the calibration parameters from linear regression (*NO2_s_1mLR2*) diminishes the mean biases for all sensors (between 1 and 7 µg/m^3). The relative expanded uncertainties become smaller.

When we look at the expanded uncertainty of the hourly sensor data *NO2_s_1mLR2* at the LV (200 µg/m^3), the UAT (140 µg/m^3) and the LAT (100 µg/m^3), the expanded uncertainty is ≤ 25 % at these levels for sensors VQS2 and VQS3. For the sensors VQS1 and VQS4 the expanded uncertainty is > 75 %. The expanded uncertainty for the daily sensor data *NO2_s_1mLR2* is also smaller for sensors VQS2 and VQS3 comparison to sensors VQS1 and VQS4. The expanded uncertainty at the LV, the UAT and the LAT for the daily sensor data *NO2_s_1mLR2* is always > than 25 %.The expanded uncertainty for these sensors is ≤ 75 % at the LV (40 µg/m), the UAT (32 µg/m^3) and the LAT (26 µg/m^3). Also for sensor VQS4 the expanded uncertainty is ≤ 75 % at the LV and at the UAT.

For the uncalibrated hourly and daily sensor data (*NO2_s_2*), the expanded uncertainty is always > 75 % at the LV, the UAT and the LAT.

7.3 Sensor data calibrated with parameters from multiple linear regression

7.3.1 Calibration parameters

Table 49: Envea Cairclip NO_2 sensor: Parameters from multiple linear regression (including NO_2 reference measurements (NO2_ref), temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	T	RH
VQS1	-6.28	0.22	0.27	-0.01*
VQS2	-7.06	0.44	0.39	-0.02
VQS3	-6.12	0.29	0.10	-0.01*
VQS4	-8.55	0.21	0.45	0.05

Variable not significant at 0.05 significance level

Table 50: Envea Cairclip NO_2 sensor: Parameters from extended multiple linear regression (including NO_2 reference measurements (NO2_ref), ozone reference measurements (O3_ref) temperature T, relative humidity (RH)) - hourly field data from February 23 2019- March 31 2019

sensor_internal_id	intercept	NO_2_ref	O_3_ref	T	RH
VQS1	-18.40	0.31	0.10	0.35	0.04
VQS2	-14.83	0.50	0.07	0.44	0.01*
VQS3	-17.37	0.37	0.10	0.18	0.04
VQS4	-8.76	0.21	0.01*	0.45	0.04

Variable not significant at 0.05 significance level

7.3.2 Comparison sensor versus reference

7.3.2.1 Time plot and scatter plots of hourly values

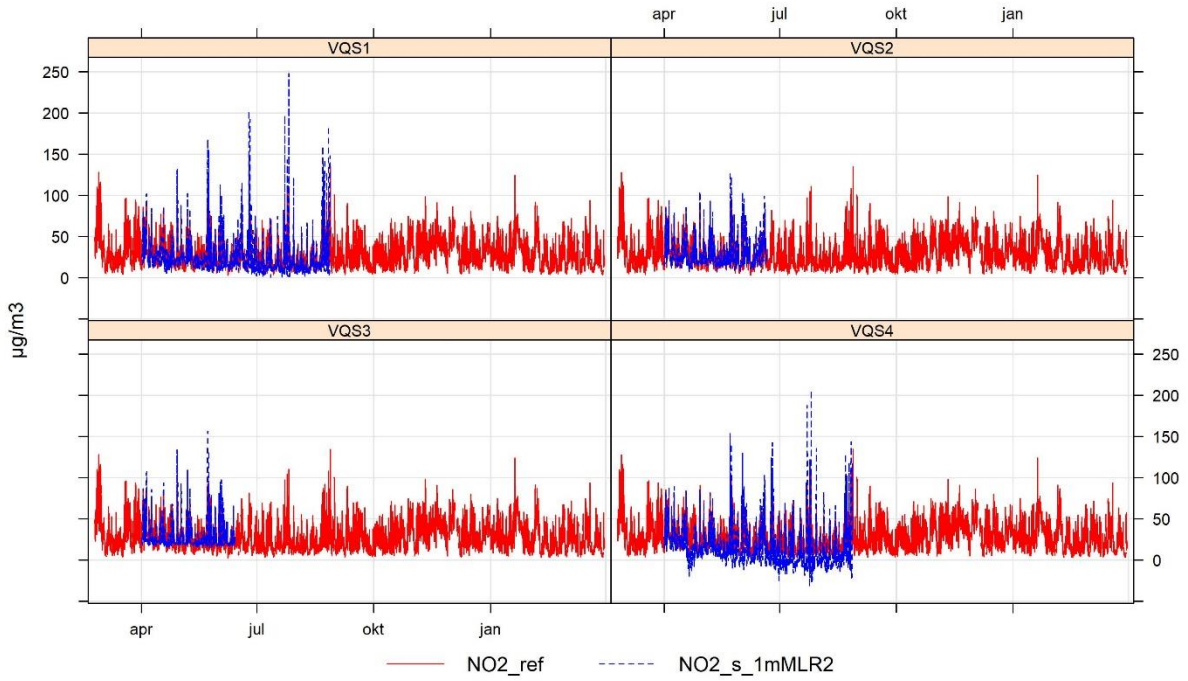


Figure 114: Envea Cairclip NO_2 sensor: Time plot of sensor hourly values calibrated with multiple linear regression model and reference values (µg/m3)

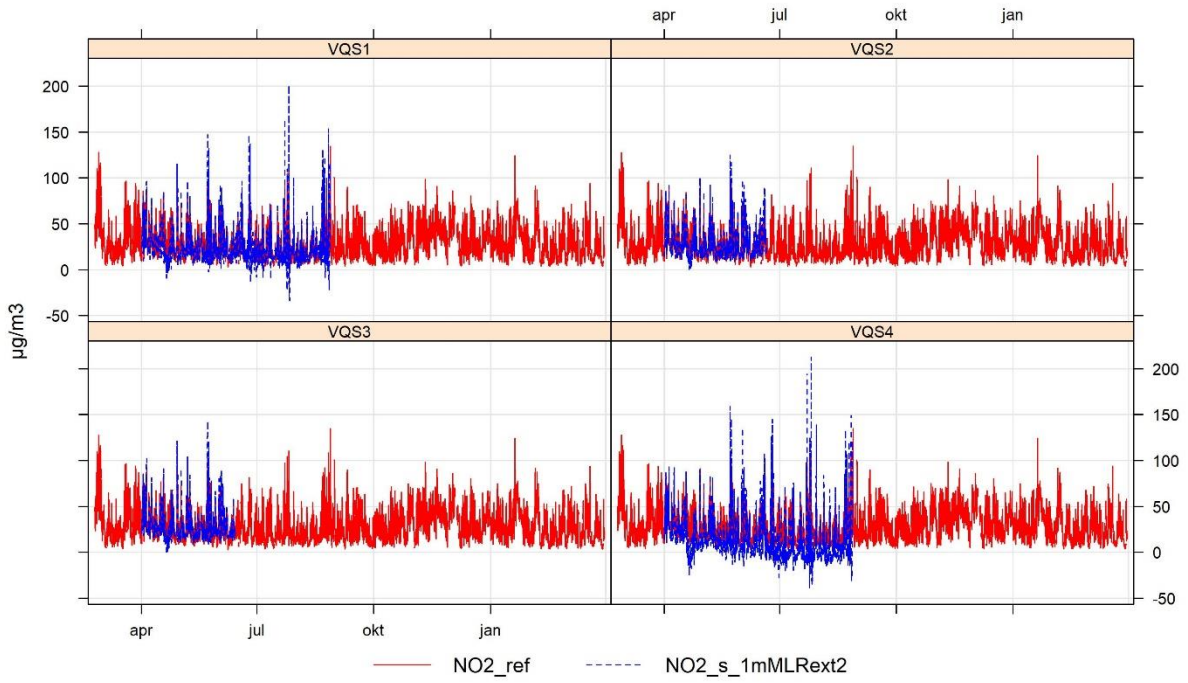


Figure 115: Envea Cairclip NO_2 sensor: Time plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

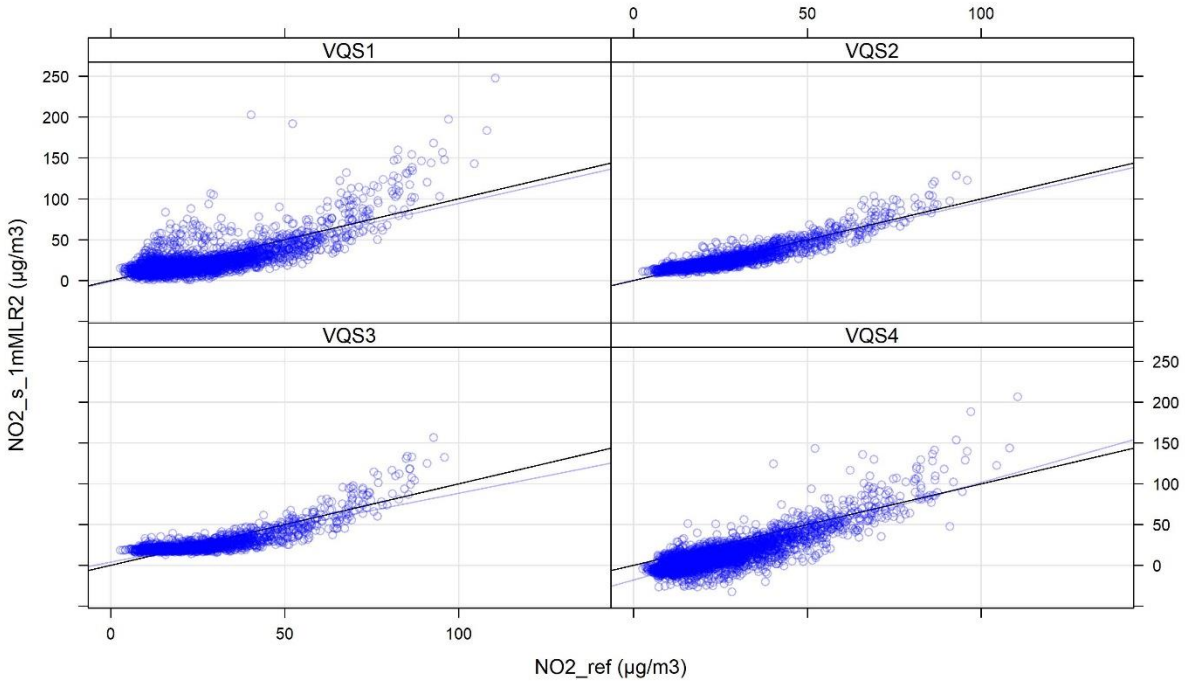


Figure 116: Envea Cairclip NO_2 sensor: Scatter plot of sensor hourly values calibrated with multiple linear regression model and reference values (µg/m³)

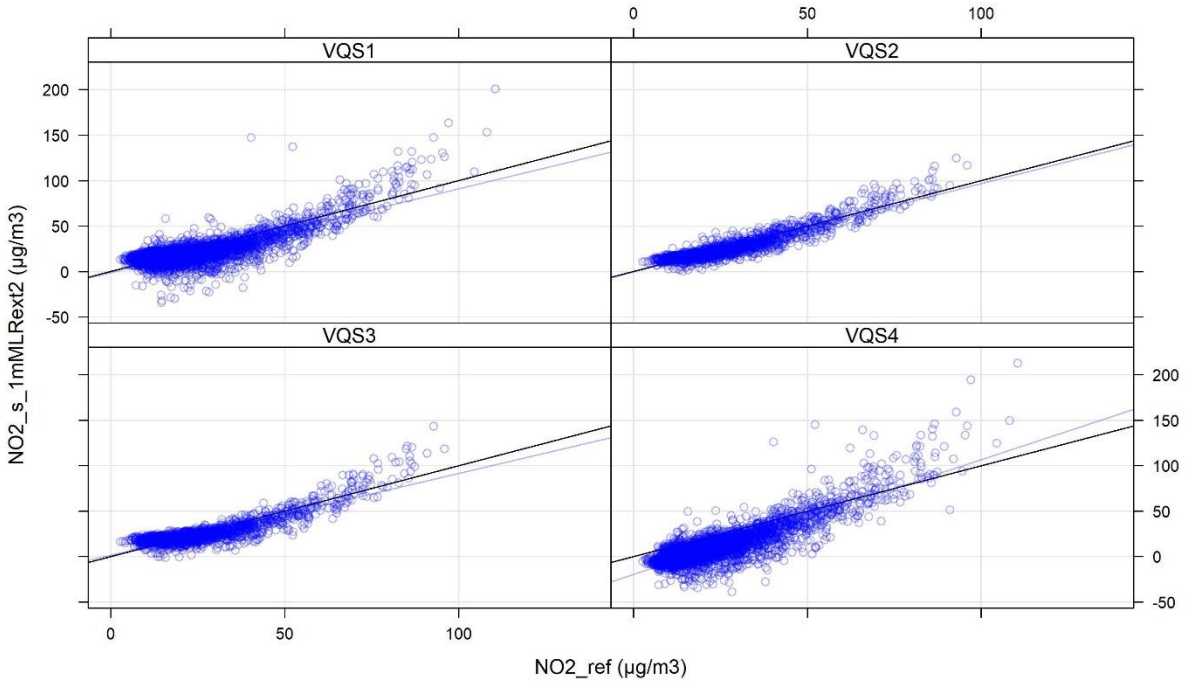


Figure 117: Envea Cairclip NO_2 sensor: Scatter plot of sensor hourly values calibrated with extended multiple linear regression model and reference values (µg/m³)

7.3.2.2 Ratio of hourly sensor values versus reference values

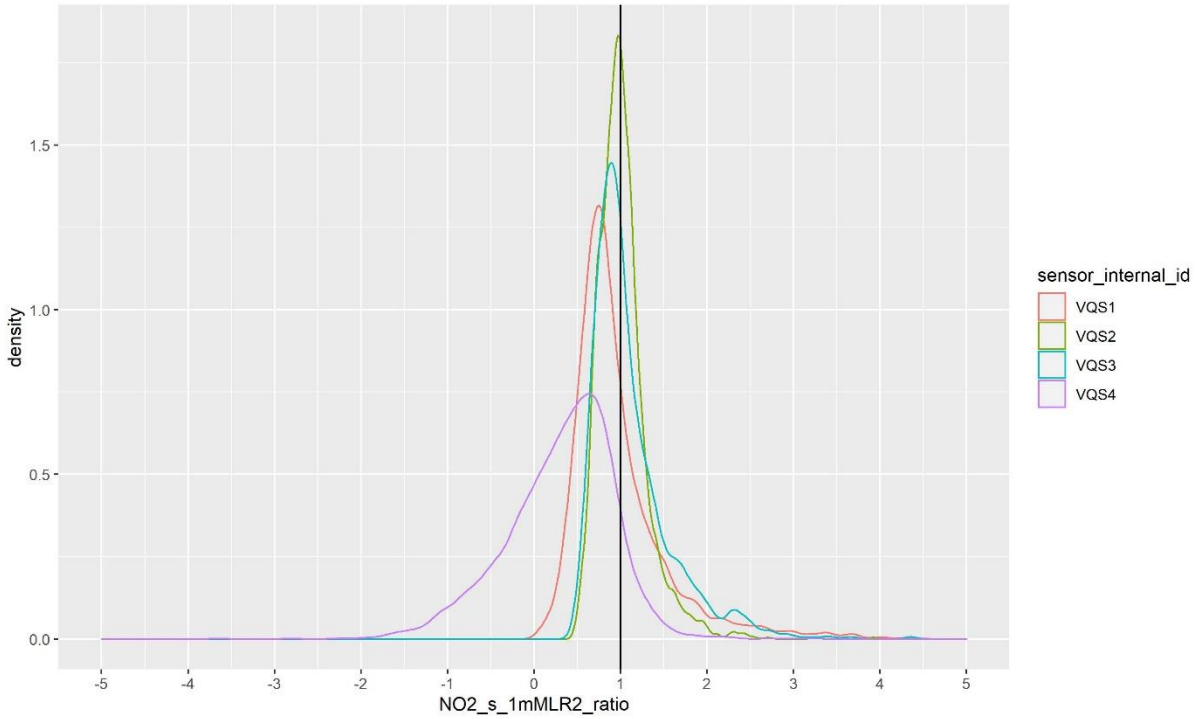


Figure 118: Envea Cairclip NO_2 sensor: Density plot of ratio sensor hourly values calibrated with multiple linear regression versus reference values

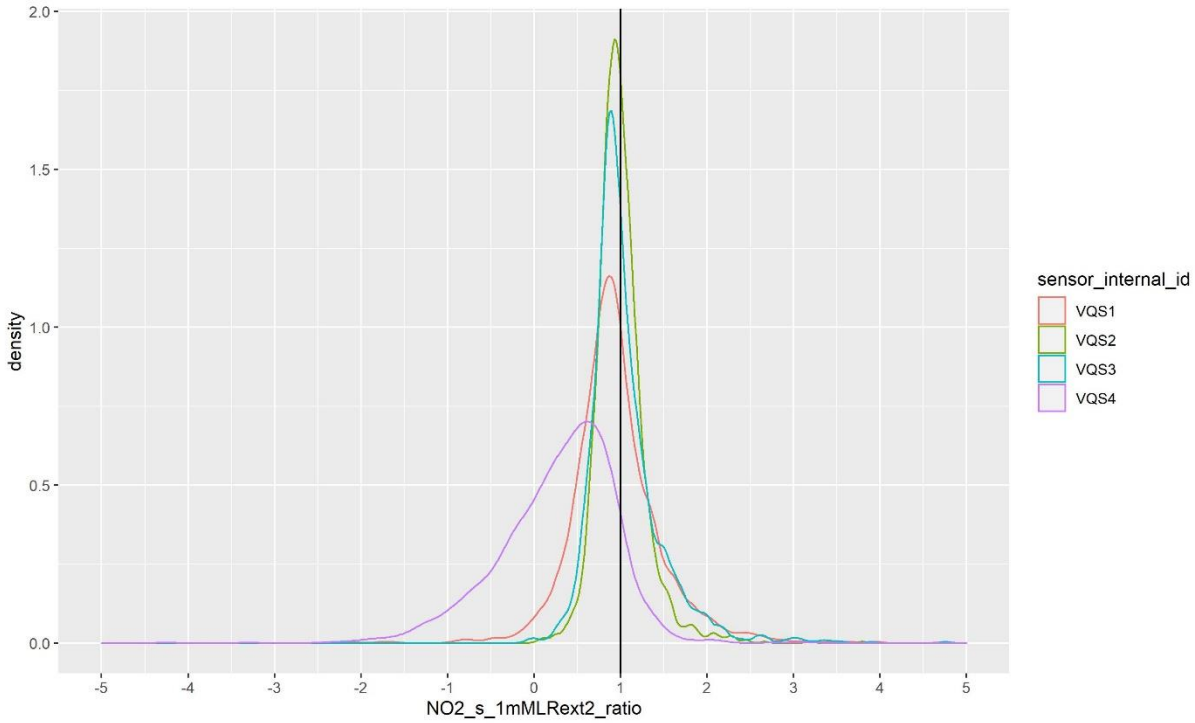


Figure 119: Envea Cairclip NO_2 sensor: Density plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values

7.3.3 Influence of time, temperature, relative humidity and O_3

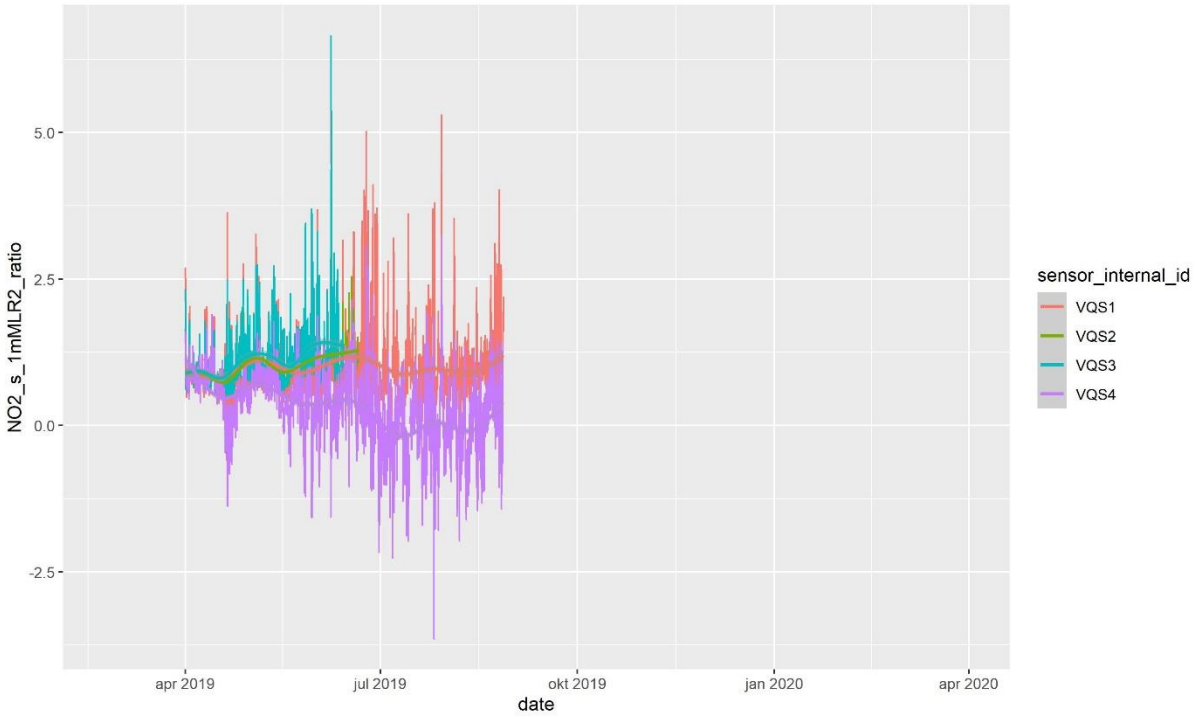


Figure 120: Envea Cairclip NO_2 sensor: Time plot of ratio sensor hourly values calibrated with multiple linear regression versus reference values (µg/m³)

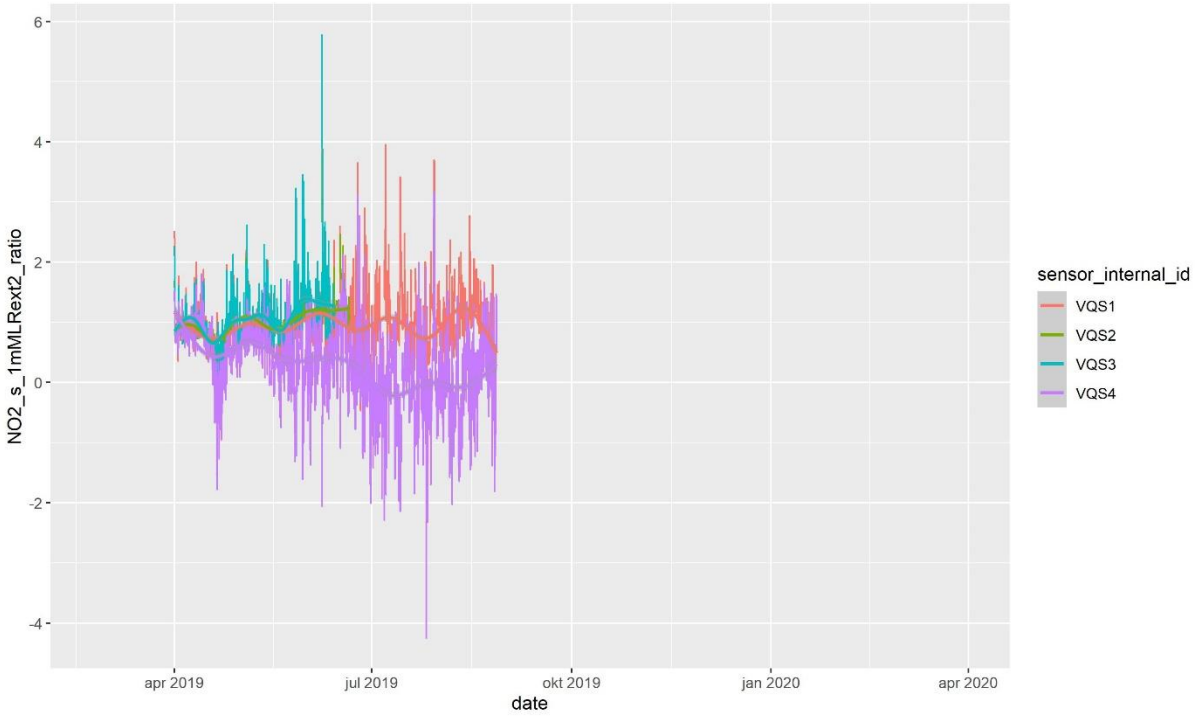


Figure 121: Envea Cairclip NO_2 sensor: Time plot of ratio sensor hourly values calibrated with extended multiple linear regression versus reference values (µg/m³)

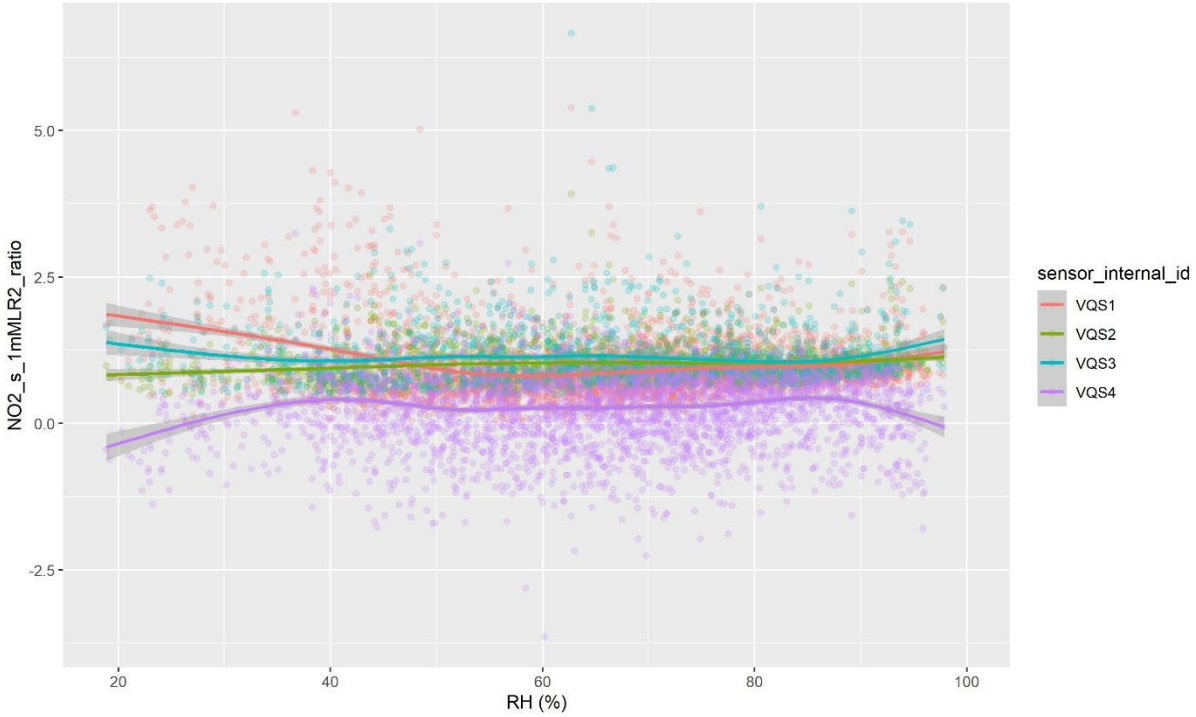


Figure 122: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with multiple linear regression versus reference values in relation to relative humidity (%)

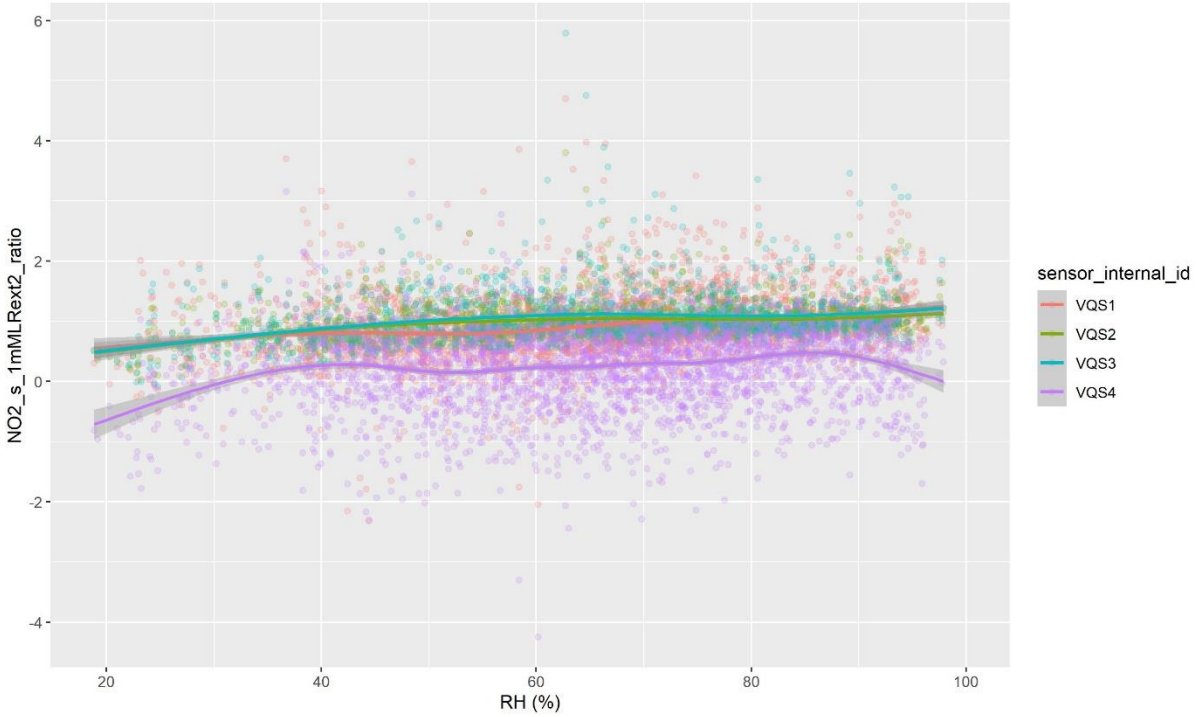


Figure 123: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to relative humidity (%)

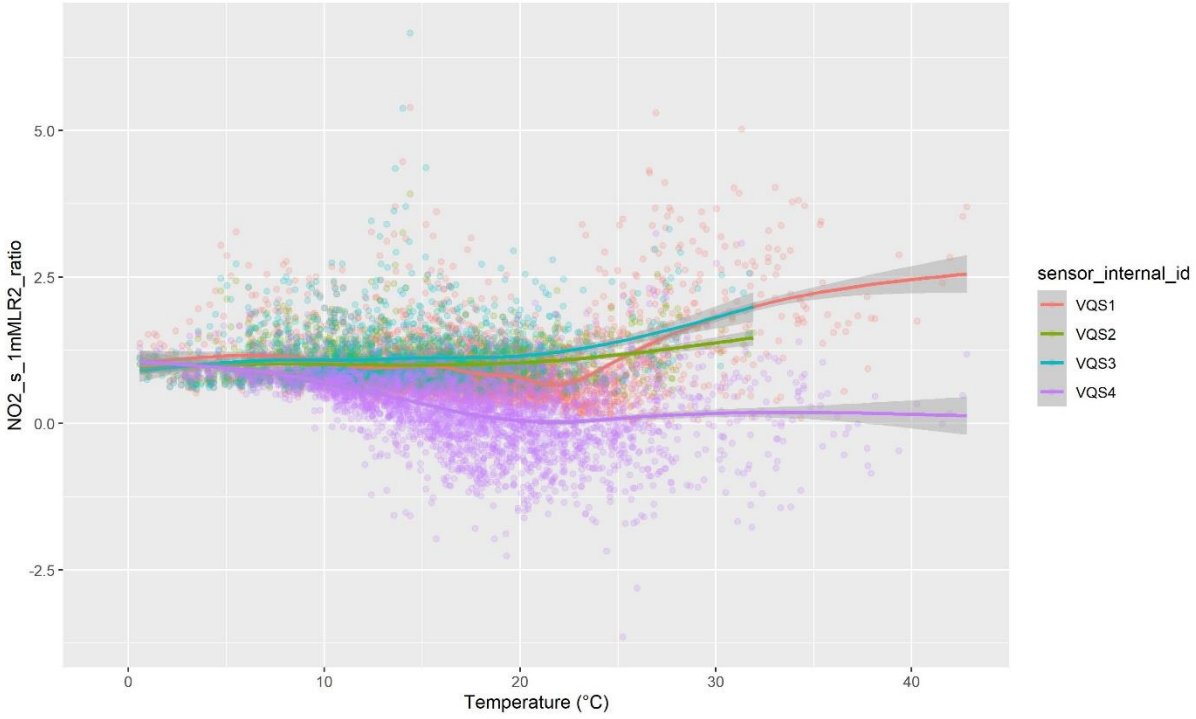


Figure 124: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with multiple linear regression versus reference values in relation to temperature (°C)

Figure 125: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to temperature (°C)

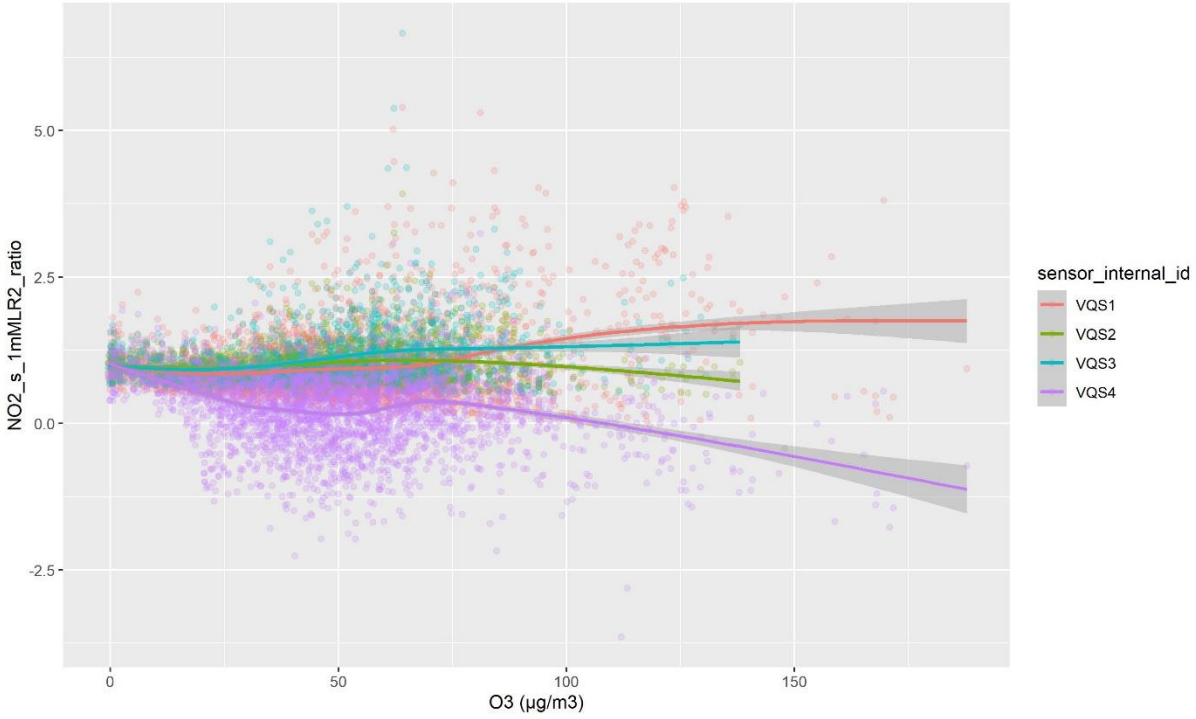


Figure 126: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with multiple linear regression versus reference values in relation to ozone (µg/m³)

Figure 127: Envea Cairclip NO_2 sensor: Scatter plot ratio sensor hourly values calibrated with extended multiple linear regression versus reference values in relation to ozone (µg/m³)

7.3.4 Descriptive parameters

Table 51: Envea Cairclip NO_2 sensor: Descriptive parameters for sensors calibrated with multiple linear regression and extended multiple linear regression. ID: sensor idea, n: number of values, R^2: coefficient of determination, Ubs: between sampler uncertainty

		Calibration		Evaluation				
	ID	n	R^2	n	mean bias ($\mu g/m^3$)	R^2	u_{bs} ($\mu g/m^3$)	u_{bs} (%)
NO_2_s_1mMLR2	VQS1	768	0.79	3301	-2.40	0.57		
NO_2_s_1mMLR2	VQS2	846	0.95	1777	-0.81	0.84		
NO_2_s_1mMLR2	VQS3	846	0.86	1645	-0.40	0.71		
NO_2_s_1mMLR2	VQS4	826	0.87	3323	-12.64	0.74		
NO_2_s_1mMLR2	all sensors			10046		0.64	18.19	84.06
NO_2_s_1mMLRext2	VQS1	672	0.90	3229	-3.25	0.66		
NO_2_s_1mMLRext2	VQS2	737	0.97	1739	-1.17	0.86		
NO_2_s_1mMLRext2	VQS3	737	0.93	1609	-1.21	0.77		
NO_2_s_1mMLRext2	VQS4	719	0.89	3251	-12.77	0.75		
NO_2_s_1mMLRext2	all sensors			9828			17.93	84.67

7.3.5 Relative expanded uncertainty

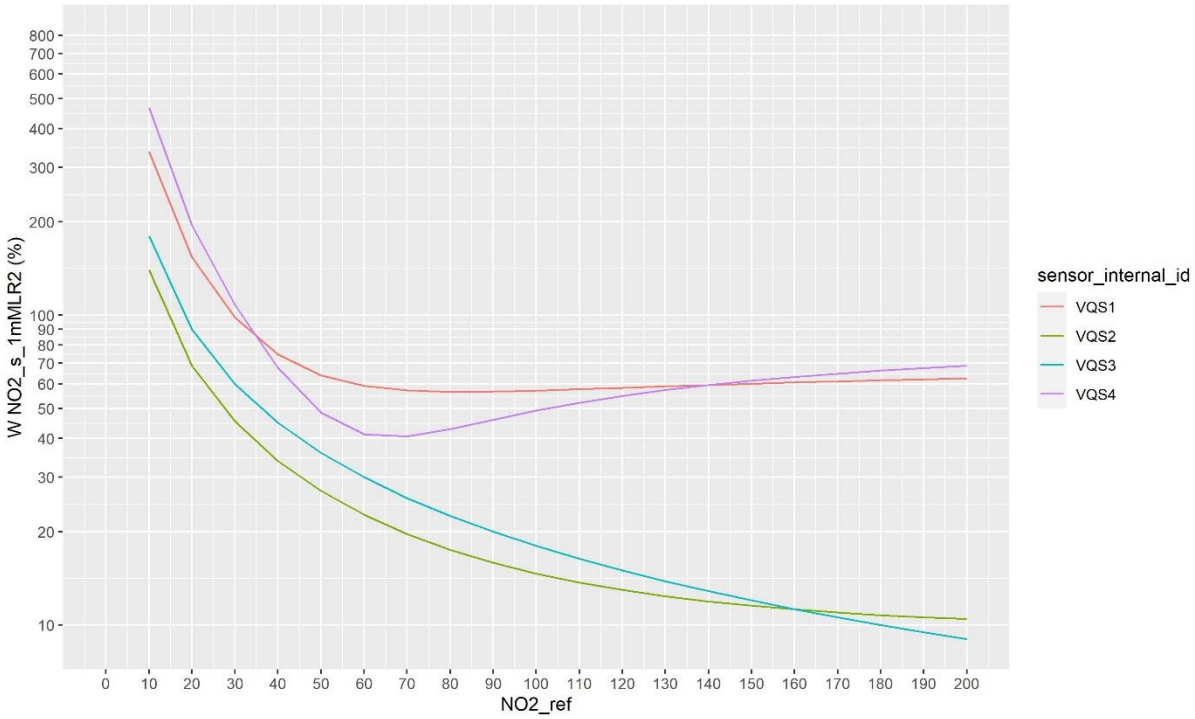


Figure 128: Envea Cairclip NO_2 sensor: Relative expanded uncertainty (W (%)) of sensor calibrated with multiple linear regression according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logarithmic scale

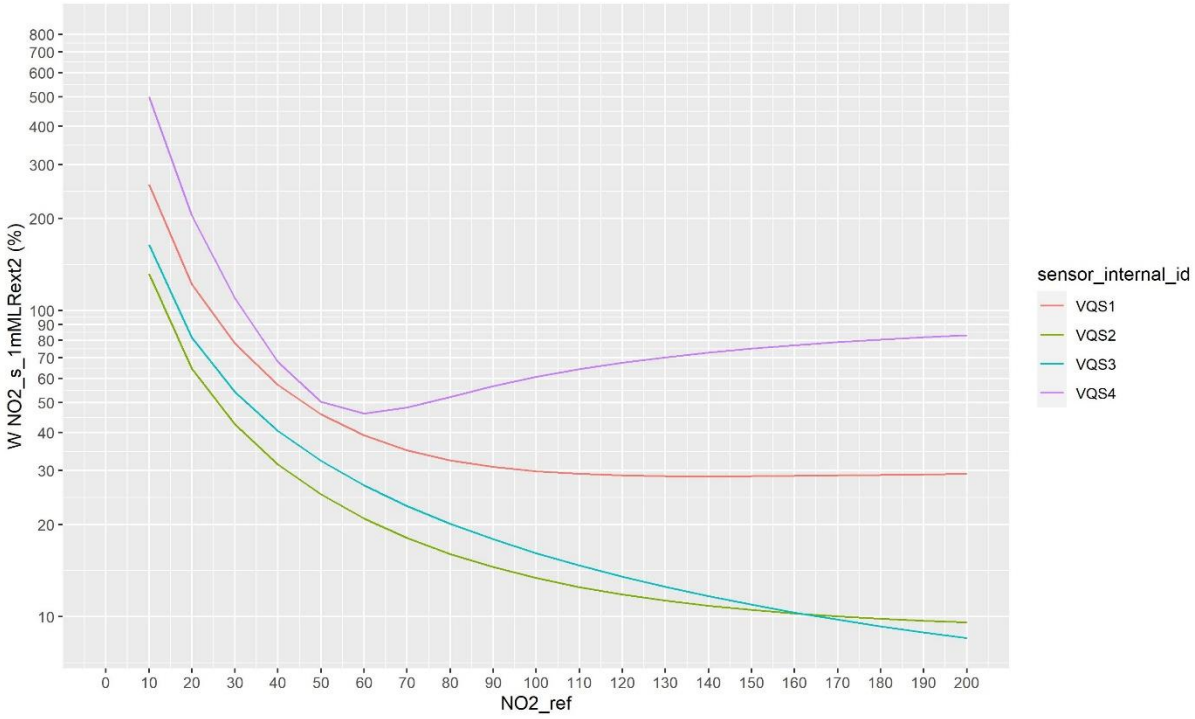


Figure 129: Envea Cairclip NO_2 sensor: Relative expanded uncertainty (W (%)) of sensor calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at hourly NO_2 reference concentrations of 10 to 200 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logarithmic scale

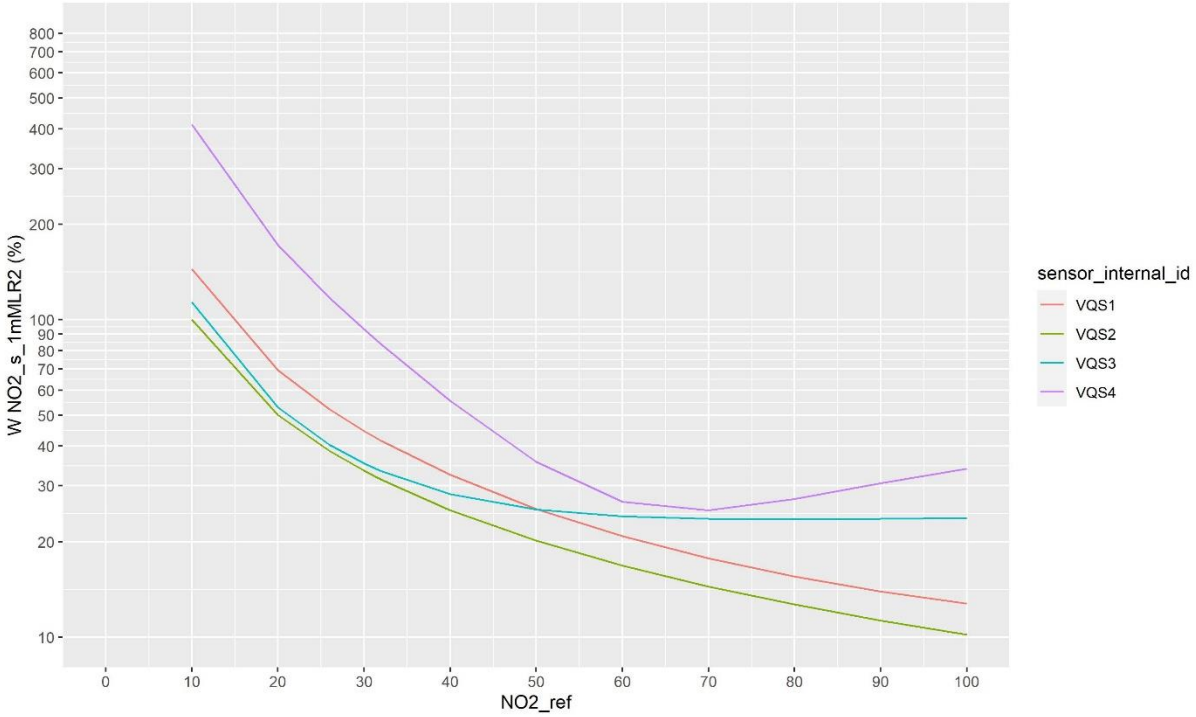


Figure 130: Envea Cairclip NO_2 sensor: Relative expanded uncertainty (W (%)) of sensors calibrated with multiple linear regression according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logaritmic scale

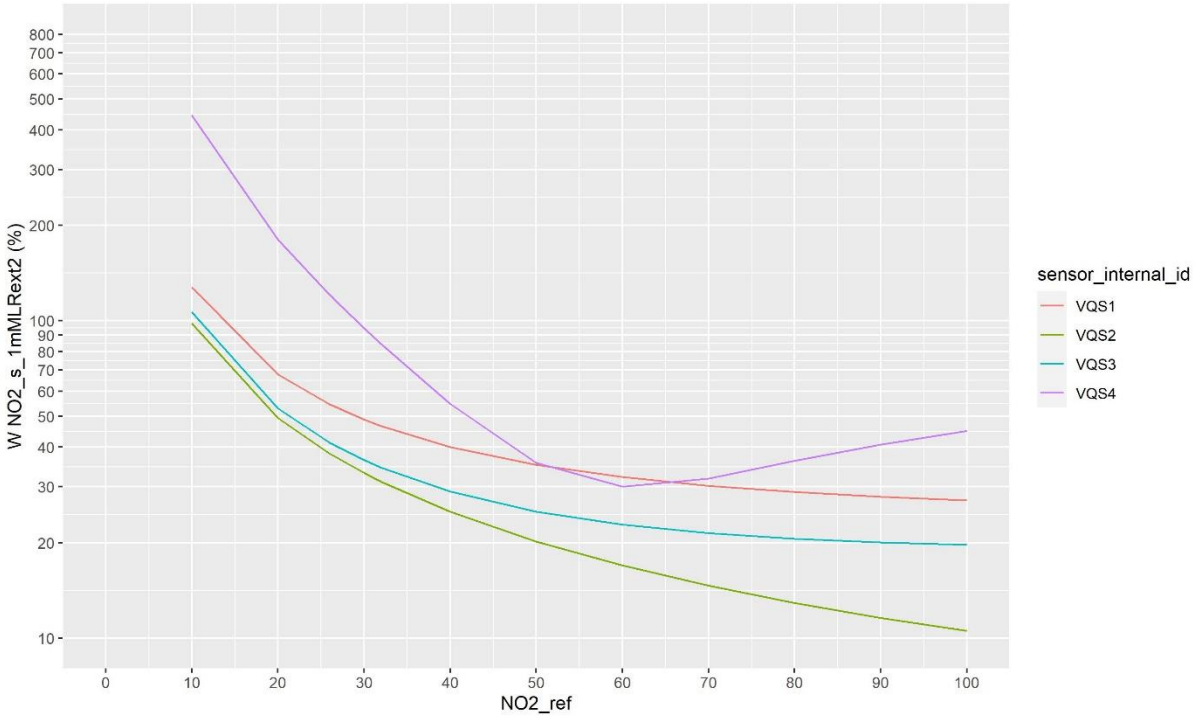


Figure 131: Envea Cairclip NO_2 sensor: Relative expanded uncertainty (W (%)) of sensors calibrated with extended multiple linear regression according to Guidance of Equivalence calculated at daily NO_2 reference concentrations of 10 to 100 µg/m³ in steps of 10 µg/m³. The relative expanded uncertainties are presented on a logaritmic scale.

Table 52: Envea Cairclip NO_2 sensor: Relative expanded uncertainty of sensors calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO_2 hourly reference concentrations of 100 µg/m³ (LAT), 140 µg/m³ (UAT) and 200 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLR2	VQS1	100	14.71	24.48	57.13
NO_2_s_1mMLR2	VQS2	100	6.77	2.85	14.68
NO_2_s_1mMLR2	VQS3	100	8.99	-0.54	18.01
NO_2_s_1mMLR2	VQS4	100	12.02	21.48	49.23
NO_2_s_1mMLRext2	VQS1	100	11.41	9.60	29.83
NO_2_s_1mMLRext2	VQS2	100	6.26	2.33	13.36
NO_2_s_1mMLRext2	VQS3	100	8.04	0.44	16.11
NO_2_s_1mMLRext2	VQS4	100	12.58	27.62	60.70
NO_2_s_1mMLR2	VQS1	140	14.71	39.01	59.56
NO_2_s_1mMLR2	VQS2	140	6.77	4.90	11.93
NO_2_s_1mMLR2	VQS3	140	8.99	-0.62	12.87
NO_2_s_1mMLR2	VQS4	140	12.02	39.92	59.56
NO_2_s_1mMLRext2	VQS1	140	11.41	16.55	28.72
NO_2_s_1mMLRext2	VQS2	140	6.26	4.29	10.84
NO_2_s_1mMLRext2	VQS3	140	8.04	1.37	11.65
NO_2_s_1mMLRext2	VQS4	140	12.58	49.47	72.92
NO_2_s_1mMLR2	VQS1	200	14.71	60.80	62.56
NO_2_s_1mMLR2	VQS2	200	6.77	7.98	10.46
NO_2_s_1mMLR2	VQS3	200	8.99	-0.74	9.02
NO_2_s_1mMLR2	VQS4	200	12.02	67.59	68.65
NO_2_s_1mMLRext2	VQS1	200	11.41	26.97	29.29
NO_2_s_1mMLRext2	VQS2	200	6.26	7.24	9.57
NO_2_s_1mMLRext2	VQS3	200	8.04	2.76	8.50
NO_2_s_1mMLRext2	VQS4	200	12.58	82.24	83.19

Table 53: Envea Cairclip NO_2 sensor: Relative expanded uncertainty of sensors calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) according to Guidance of Equivalence calculated at NO_2 daily reference concentrations of 26 µg/m³ (LAT), 32 µg/m³ (UAT) and 40 µg/m³ (LV)

	ID	NO_2_ref (µg/m³)	random term (µg/m³)	bias (µg/m³)	expanded uncertainty (%)
NO_2_s_1mMLR2	VQS1	26	6.19	-2.79	52.19
NO_2_s_1mMLR2	VQS2	26	4.90	-1.07	38.57
NO_2_s_1mMLR2	VQS3	26	5.24	-0.10	40.35
NO_2_s_1mMLR2	VQS4	26	8.02	-12.99	117.43
NO_2_s_1mMLRext2	VQS1	26	6.20	-3.43	54.51
NO_2_s_1mMLRext2	VQS2	26	4.78	-1.30	38.12
NO_2_s_1mMLRext2	VQS3	26	5.28	-0.98	41.35
NO_2_s_1mMLRext2	VQS4	26	8.67	-13.09	120.81
NO_2_s_1mMLR2	VQS1	32	6.19	-2.43	41.55
NO_2_s_1mMLR2	VQS2	32	4.90	-1.10	31.37
NO_2_s_1mMLR2	VQS3	32	5.24	-0.95	33.31
NO_2_s_1mMLR2	VQS4	32	8.02	-10.73	83.69
NO_2_s_1mMLRext2	VQS1	32	6.20	-4.13	46.57
NO_2_s_1mMLRext2	VQS2	32	4.78	-1.37	31.10
NO_2_s_1mMLRext2	VQS3	32	5.28	-1.58	34.47
NO_2_s_1mMLRext2	VQS4	32	8.67	-10.35	84.40
NO_2_s_1mMLR2	VQS1	40	6.19	-1.96	32.45
NO_2_s_1mMLR2	VQS2	40	4.90	-1.13	25.13
NO_2_s_1mMLR2	VQS3	40	5.24	-2.10	28.24
NO_2_s_1mMLR2	VQS4	40	8.02	-7.71	55.60
NO_2_s_1mMLRext2	VQS1	40	6.20	-5.07	40.04
NO_2_s_1mMLRext2	VQS2	40	4.78	-1.47	25.02
NO_2_s_1mMLRext2	VQS3	40	5.28	-2.37	28.95
NO_2_s_1mMLRext2	VQS4	40	8.67	-6.70	54.78

Table 54: Envea Cairclip NO_2 sensor: Parameters of orthogonal regression of hourly and daily sensor data calibrated with multiple linear regression (NO2_S_1mMLR2) and extended multiple linear regression (NO2_S_1mMLRext2) versus reference NO2

		hourly values		daily values	
	ID	slope	intercept (µg/m³)	slope	intercept (µg/m³)
NO_2_s_1mMLR2	VQS1	1.36	-11.83	1.06	-4.32
NO_2_s_1mMLR2	VQS2	1.05	-2.28	1.00	-0.97
NO_2_s_1mMLR2	VQS3	1.00	-0.34	0.86	3.61
NO_2_s_1mMLR2	VQS4	1.46	-24.64	1.38	-22.81
NO_2_s_1mMLRext2	VQS1	1.17	-7.77	0.88	-0.40
NO_2_s_1mMLRext2	VQS2	1.05	-2.59	0.99	-0.98
NO_2_s_1mMLRext2	VQS3	1.02	-1.88	0.90	1.58
NO_2_s_1mMLRext2	VQS4	1.55	-27.00	1.46	-24.98

7.3.6 Conclusions

Calibration of the sensor data with the parameters from the MLR functions (*NO2_s_1mMLR* and *NO2_s_1mMLRext2*) leads to higher R^2 in comparison with the sensor data calibrated with the parameters from the LR function (*NO2_s_1mLR*) . The mean biases become negative, especially for sensor VQS4. The relative between sampler uncertainties become higher. When we look at the scatter plots of the ratio sensor data versus reference data in relation to temperature, relative humidity and O_3, we see that the ratios are higher in comparison with the uncalibrated sensor data. This is due to the fact that the uncalibrated data largely underestimate the NO_2 concentrations. The data of sensor VQS4 drift in function of time after calibration with the parameters from the MLR regression functions.

The relative expanded uncertainties of the hourly and the daily sensor data calibrated with the parameters from the MLR are almost always smaller than these of the sensor data calibrated with the parameters from the LR at the limit values and the assessment thresholds.

When we compare the sensor data calibrated with the parameters from the MLR with O_3 (*NO2_s_1mMLRext2*) to the sensor data calibrated with the parameters from the MLR without O_3 (*NO2_s_1mMLR*) we notice higher R^2 (between 0.57 and 0.84 for sensor data *NO2_s_1mMLR* and between 0.66 and 0.86 for sensor data *NO2_s_1mMLRext2*), comparable negative biases (between -13 and -1 µg/m^3) and comparable between sampler uncertainties (84 % for sensor data *NO2_s_1mMLR* and 85 % for sensor data *NO2_s_1mMLRext2)*.

When we look at the expanded uncertainty of the hourly sensor data *NO2_s_1mMLR2 and NO2_s_1mMLRext2* at the LV (200 µg/m^3), the UAT (140 µg/m^3) and the LAT (100 µg/m^3), the expanded uncertainty is ≤ 25 % at these levels for sensors VQS2 and VQS3. For the sensors VQS1 and VQS4 the expanded uncertainty is ≤ 75 %, except for sensor VQS4 after calibration with MLR with O_3 (*NO2_s_1mMLRext2)* at the LV (200 µg/m^3).

The expanded uncertainties for the daily sensor data *NO2_s_1mMLR2* and *NO2_s_1mMLR2ext2* are ≤ 75 % for all sensors at the LV (40 µg/m), the UAT (32 µg/m^3) and the LAT (26 µg/m^3), except for sensor VQS4 at the LAT and the UAT. The expanded uncertainty is 25 % for sensor VQS2 at the LV. For the other sensor and the other levels the expanded uncertainties are > 25 %.

The relative expanded uncertainties for the hourly sensor data *NO2_s_1mMLRext2* are smaller in comparison to *NO2_s_1mMLR* at the limit values and assessment thresholds, except for sensor VQS4. The relative expanded uncertainties for the daily sensor data *NO2_s_1mMLR* and *NO2_s_1mMLRext2* are very comparable at the LV, UAT and LAT.

VAQUUMS

Field Evaluation
NO_2 sensors

General conclusions

8 GENERAL CONCLUSIONS

The raw data of the different sensors were manually validated. Both negative and positive peaks occurred frequently in the raw sensor data. When these peaks occurred after a restart of the measurements or a technical intervention, they were marked as invalid. Other peaks were marked as suspicious when they were remarkable higher or lower than the values of the other sensors.

A lot of negative values occur in the raw sensor data of the sensors **Alphasense B43F**. These negative values are present on the same moments for all the sensors. Therefore these peaks were not removed.

A lot of negative and positive peaks occurred in the raw data of the sensors **Membrapor C20**. It was not possible to remove these peaks manually, so they were marked suspicious automatically when higher than 200 µg/m^3 or lower than -100 µg/m^3. When looking at the time plots, we noticed a drop in the data of one sensor from December 15 2019 on. We also saw a lot of remaining peaks in the data of the other sensors from December on. The data from December 1, 2019 until March 30, 2020 were marked suspicious.

The **Envea Cairclip** sensors have limited data (until June- August 2019) due to technical issues and a life time of only one year.

The uncalibrated data from the sensors **Citytech 3E50**, **MembraporC1** and **Membrapor C20** showed no or almost no correlation with the reference NO_2 data. Only after calibration with the parameters of the multiple linear regression (MLR) using relative humidity, temperature and O_3 as variables, a correlation between the calibrated sensor data and reference NO_2 was found. The field campaign data from February 23, 2019 - March 31, 2019 were used to establish the calibration function.

The highest R^2 for the **Citytech 3E50** sensors after MLR calibration is 0.7. The R^2 is much smaller for the two other sensors (0.24). The mean biases of the calibrated sensor data are very negative: between -28 and -21 µg/m^3.

After calibration with parameters from MLR, the R^2 varies between 0.50 and 0.69 for the **Membrapor C1** sensors. The mean biases of the calibrated sensor data vary between -22 and 1 µg/m^3.

The R^2 for the **Membrapor C20** sensors after MLR calibration are 0.78, 0.71, 0.52 and 0.21. This latest R^2 belongs to the sensor VQL2 which also showed diverging behavior during the laboratory test. The mean biases of the calibrated sensor data vary between -8 and 19 µg/m^3 (-8 and 4 µg/m^3 without sensor VQL2).

The between sensor uncertainties of these different sensortypes after calibration are: 34 µg/m^3 (653 %) for the **Citytech 3E50** sensors, 18 µg/m^3 (98 %) for the **Membrapor C1** sensors and 21 µg/m^3 (68 %) for the **Membrapor C20** sensors. Elimination of the sensor VQL2 would improve the between sensor uncertainty for the membraporC20 sensors.

The **Alphasense B43F** and **Envea Cairclip** sensors show a correlation with the reference method without calibration. The R^2 for the uncalibrated Alphasense sensors varies between 0.23 and 0.58 and for the uncalibrated Envea Cairclip sensors between 0.48 and 0.82.

For the **Alphasense B43F** sensors correlation improves by including temperature and relative humidity in the MLR calibration functions.

Adding O_3 to the MLR calibration function improves correlation even further. The R^2 after calibration varies between 0.36 and 0.64. Uncalibrated sensors show negative mean biases between -14 and -5 µg/m^3. After calibration we see positive mean biases between 5 and 10 µg/m^3. The between sensor uncertainty is 19 µg/m^3 before calibration (91 %) and 15 µg/m^3 (41 %) after calibration.

Correlation for the **Envea Cairclip** sensors improves by including temperature and relative humidity in the MLR calibration function.

Adding O_3 to the MLR calibration function further improves correlation. The R^2 after calibration varies between 0.66 and 0.86. Uncalibrated sensors data show negative mean biases between -28 and -21 µg/m^3. After calibration with the parameters of MLR with O_3 we see mean biases between -13 and -1 µg/m^3 (-3 and -1 µg/m^3 without sensor VQS4). The between sensor uncertainty is 18 µg/m^3 (85 %) after calibration. Before calibration the between sensor uncertainty was only 5 µg/m^3, but this is related to the high underestimation of NO_2 concentrations of the uncalibrated sensor data. Elimination of the sensor VQS4 would probably improve the between sensor uncertainty for the Envea sensors. Sensor VQS4 showed diverging behaviour during the laboratory test.

Figure x until x show for the uncalibrated and calibrated sensors of the different types the performance characteristics R^2 and mean bias. In figure x the between sensor uncertainty is shown. Figure x and x give the relative expanded uncertainty for the hourly values at 200 µg/m^3 and for the daily values at 40 µg/m^3. These performance characteristics are only shown when the R^2 between the (calibrated) sensor data and the reference data are higher than 0.1.

Figure x shows that after calibrating the **Citytech 3E50,** the **Membrapor C1** and the **Membrapor C20** sensors with the MLR parameters with O_3, the expanded uncertainty of the hourly sensor data at 200 µg/m^3 of some of the individual sensors are smaller than 75 %, but none of the individual sensors have an expanded uncertainty smaller than 25 %. The expanded uncertainty of the daily sensor data at 40 µg/m^3 after calibration are also smaller than 75 % for some of the individual sensors of the sensor types Membrapor C1 and Membrapor C20, but always higher than 75 % for the sensor type Citytech 3E50.

For the **Alphasense B43F** sensors calibration with the MLR parameters with O_3 gives the lowest expanded uncertainties, both for the hourly and the daily sensor data. The expanded uncertainty at 200 µg/m^3 of the hourly values after calibration is smaller than 25 % for four of the five sensors. The expanded uncertainty of the fifth sensor is 92 %. The expanded uncertainty of the daily values at 40 µg/m^3 varies between 33 and 40 % for four of the five sensors. The expanded uncertainty of the fifth sensor is 76 %.

For the **Envea Cairclip** sensors calibration with the MLR parameters with O_3 gives the lowest expanded uncertainties for the hourly sensor data at 200 µg/m^3, except for sensor VQS4. For this sensor calibration with the MLR parameters without O_3 gives a smaller expanded uncertainty. The expanded uncertainty at 200 µg/m^3 of the hourly values after calibration with the MLR parameters without O_3 is smaller than 25 % for two of the four sensors and smaller than 75 % for all four sensors. After calibration with the MLR parameters with O_3, the same conclusion applies, except that one of the four sensors (VQS4) has an expanded uncertainty higher than 75 %. The expanded uncertainties at 40 µg/m^3 of the daily values are very similar after calibration with the MLR parameters with or without O_3: one of the four sensors has an expanded uncertainty of 25 %, the other three sensors have an expanded uncertainty smaller than 75 %, but higher than 25 %.

All studied sensor types need a calibration in the field in order to obtain the best performance. For the **Citytech 3E50** sensors, the **Membrapor C1** sensors, the **Membrapor C50** and the **Alphasense B43F** sensors, calibration with the parameters from a MLR function with temperature, relative humidity and reference O_3 give the best results. For the **Envea Cairclip** sensors MLR calibration that includes O_3 also gives the best results for most sensors.

The reference O_3 data needed at the measurement location can possibly be replaced by sensor O_3 data, modelled O_3 data or reference O_3 data from a nearby measurement station.

The calibration functions were determined for every single sensor of a sensor type. For most sensor types there is some degree of variability in the parameters of the LR and MLR calibration functions between the sensors. This makes it unlikely that one calibration function for the different sensors of a sensor types can be used in future.

An important final remark is that the calibration and the evaluation of these sensors was performed at the same measurement site in Borgerhout. We therefore have no information on how the sensors - calibrated with the calibration functions established at the measurement site of Borgerhout - would perform at other locations.

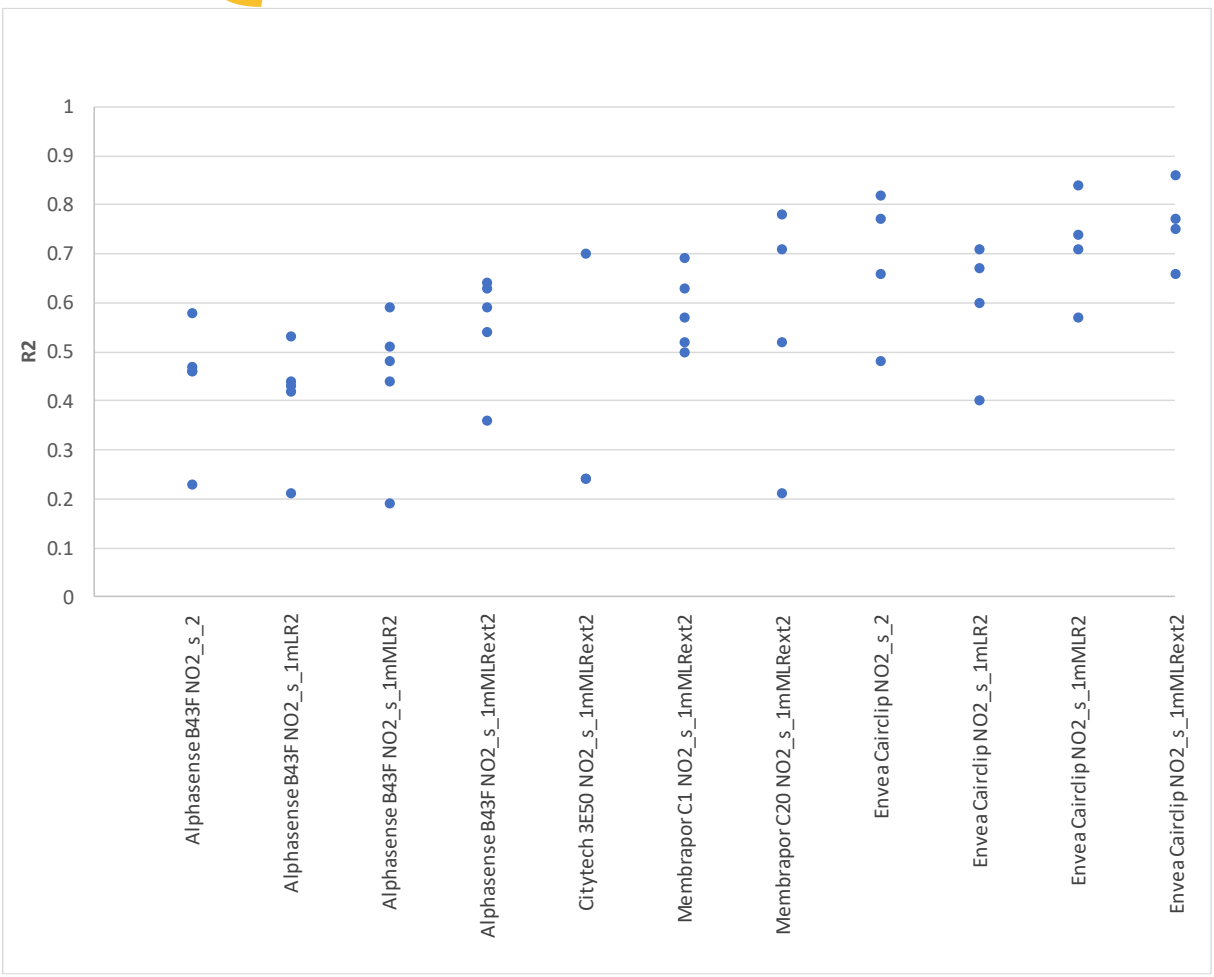


Figure 132: Summary: R^2 for the hourly sensor data for different sensor types and different calibrations. Uncalibrated (NO2_S_2), Calibrated with linear regression parameters (NO2_S_1mLR2), calibrated with multiple linear regression (NO2_S_1mMLR2) and calibrated with extended multiple linear regression (NO2_S_1mMLRext2)

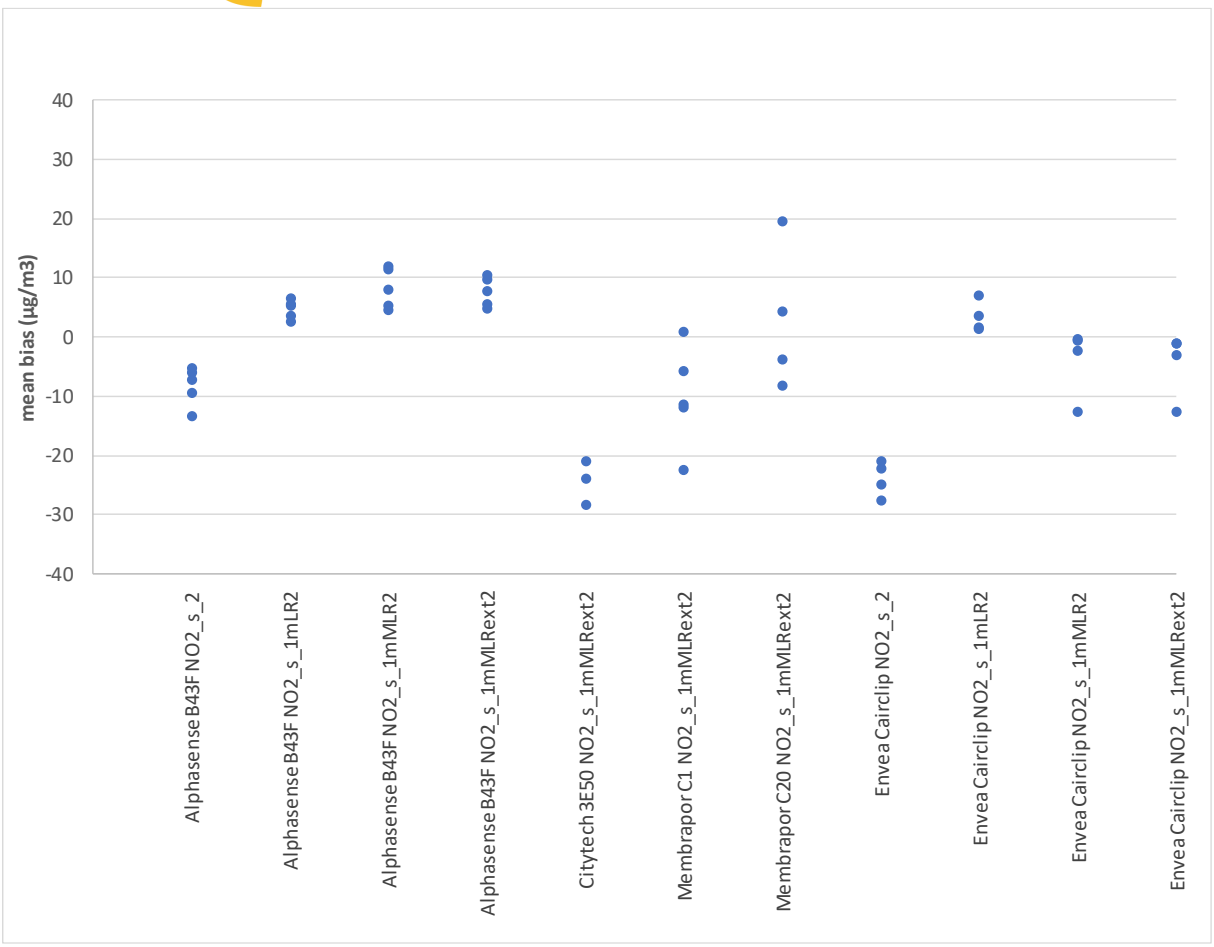


Figure 133: Summary: Mean bias (µg/m³) for the hourly sensor data for different sensor types and different calibrations. Uncalibrated (NO2_S_2), Calibrated with linear regression parameters (NO2_S_1mLR2), calibrated with multiple linear regression (NO2_S_1mMLR2) and calibrated with extended multiple linear regression (NO2_S_1mMLRext2)

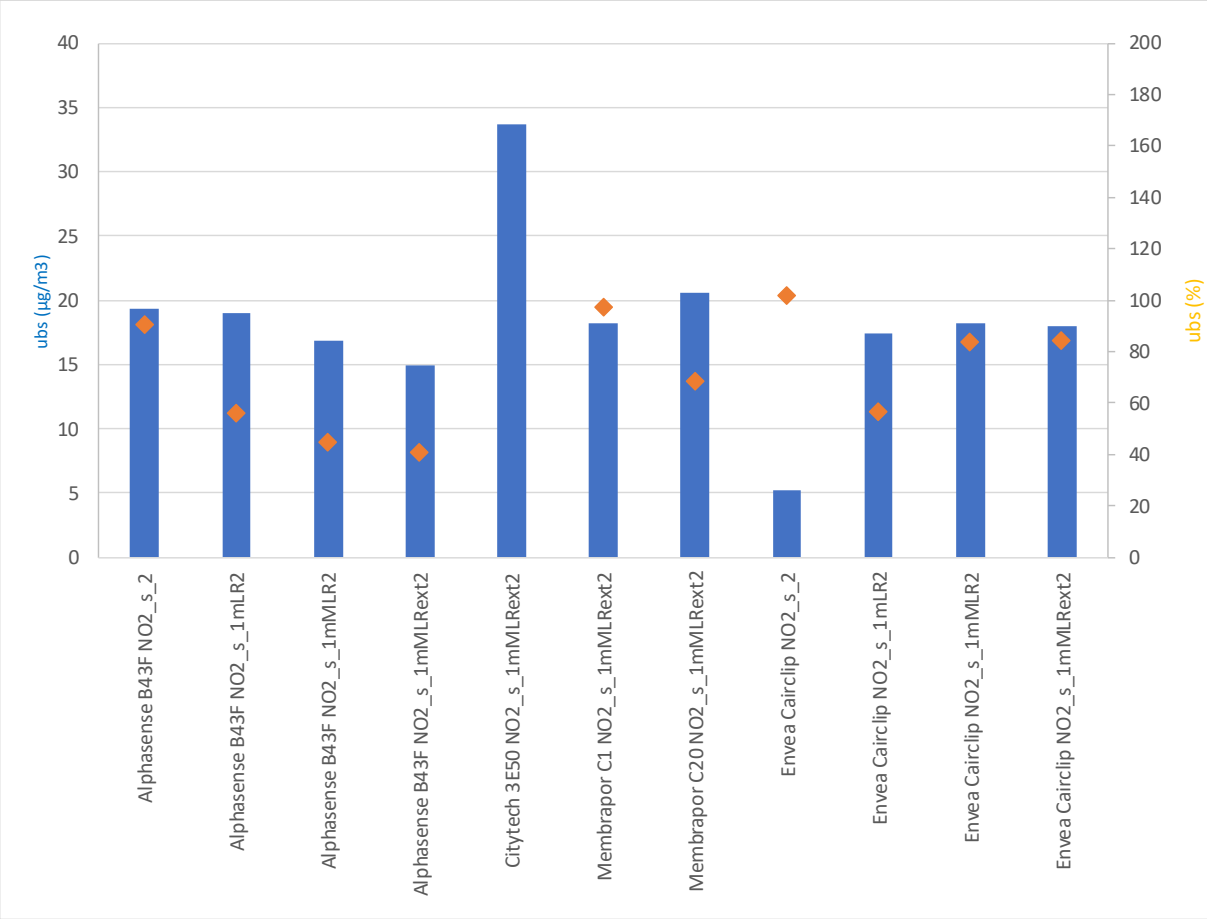


Figure 134: Summary: Between sensor uncertainty (µg/m³ and %) for the hourly sensor data for different sensor types and different calibrations. Uncalibrated (NO2_S_2), Calibrated with linear regression parameters (NO2_S_1mLR2), calibrated with multiple linear regression (NO2_S_1mMLR2) and calibrated with extended multiple linear regression (NO2_S_1mMLRext2). Note that the relative between uncertainty of Citytech 3E50 NO_2_s_1mMLRext2 (652.6 %) is not shown

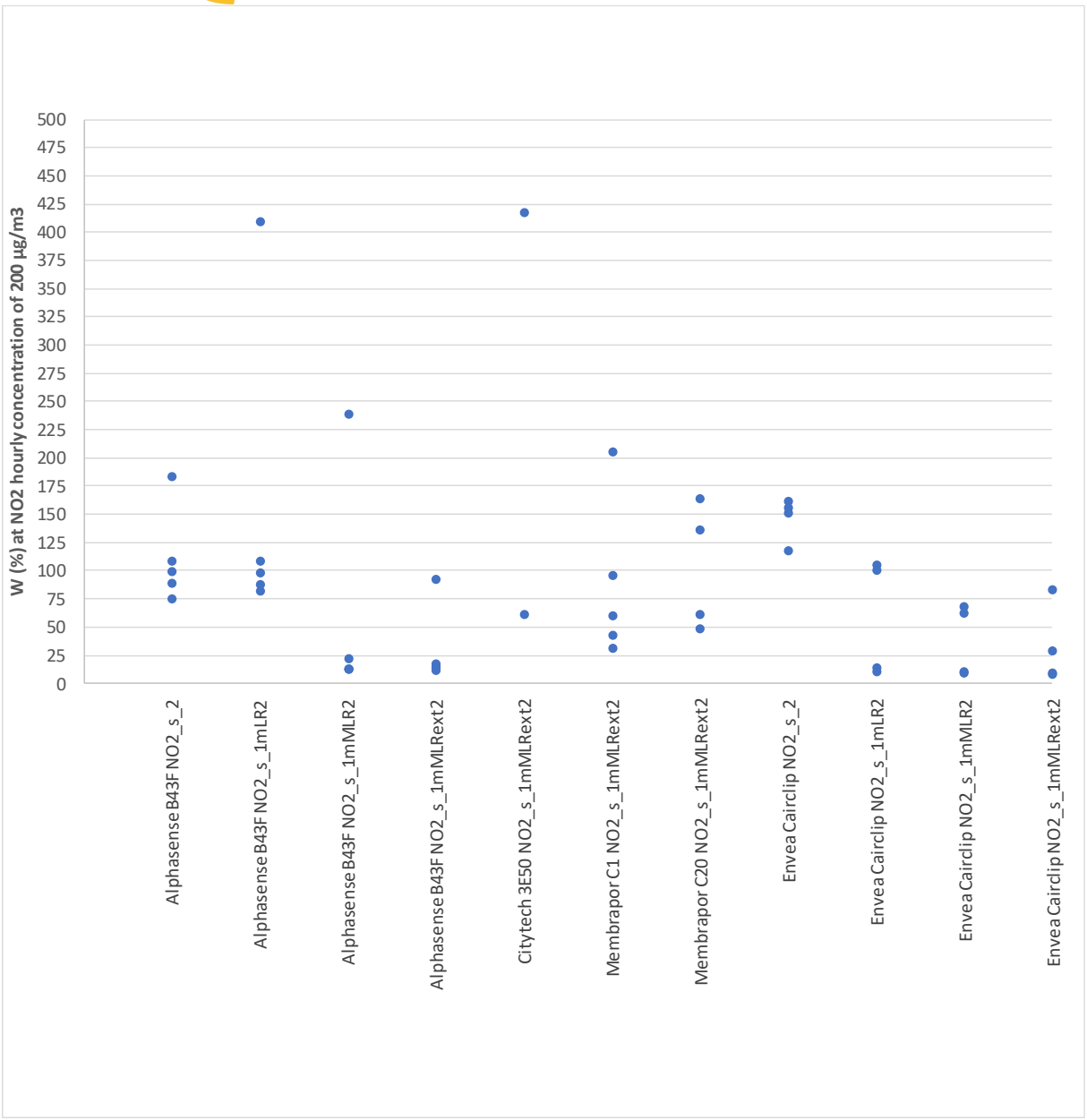


Figure 135: Summary: Relative expanded uncertainty (%) for the hourly uncalibrated and calibrated sensor data at 200 µg/m³ for different sensor types and different calibrations. Uncalibrated (NO2_S_2), Calibrated with linear regression parameters (NO2_S_1mLR2), calibrated with multiple linear regression (NO2_S_1mMLR2) and calibrated with extended multiple linear regression. Note that sensor VQI2 of Citytech 3E50 (1078 %) is not shown.

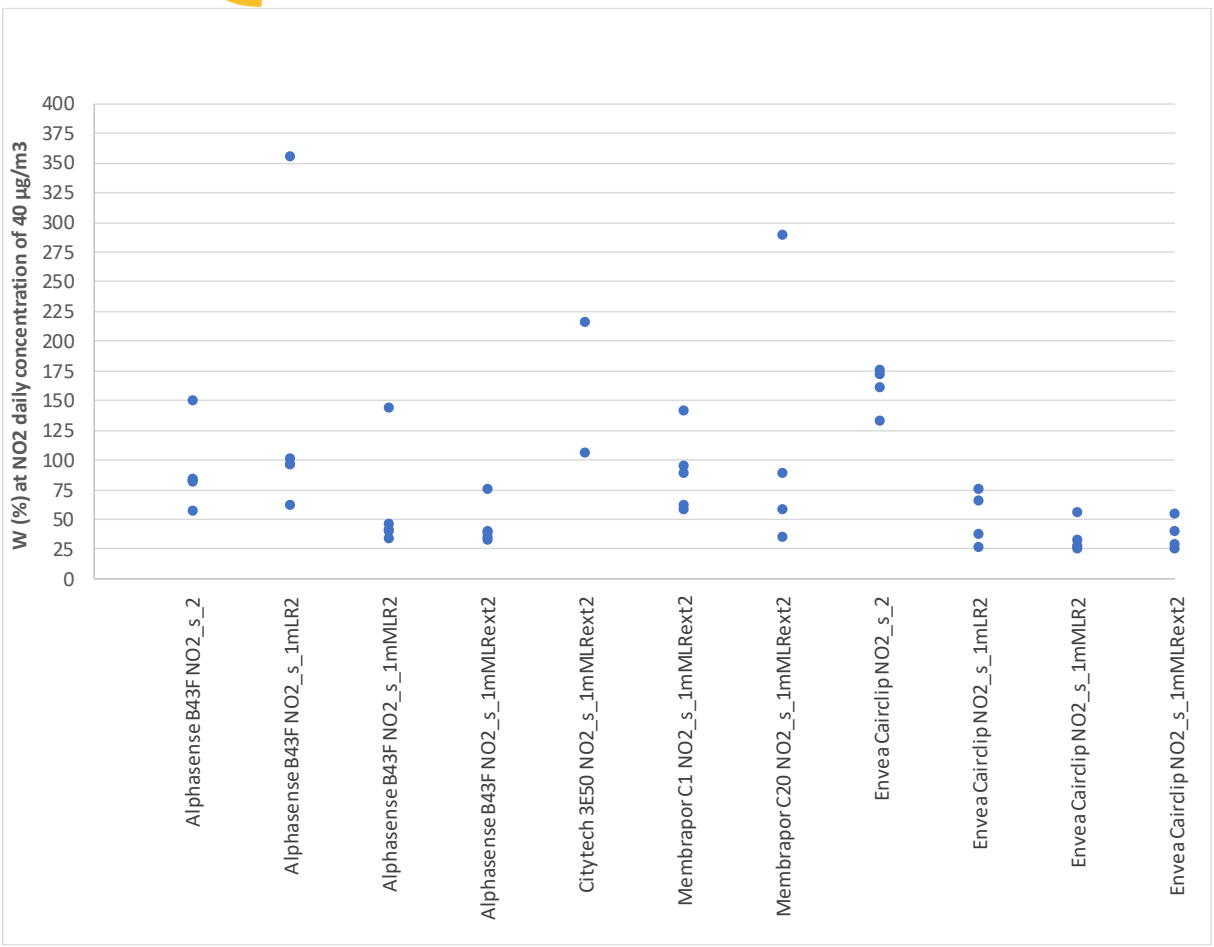


Figure 136: Summary: Relative expanded uncertainty (%) for the daily uncalibrated and calibrated sensor data at 40 µg/m³ for different sensor types and different calibrations. Uncalibrated (NO2_S_2), Calibrated with linear regression parameters (NO2_S_1mLR2), calibrated with multiple linear regression (NO2_S_1mMLR2) and calibrated with extended multiple linear regression. Note that sensor VQI2 of Citytech 3E50 (644 %) is not shown.

VAQUUMS

Appendices

Performance evaluation of five low-cost nitrogen dioxide sensors in the field

Author: Christina Matheeussen

9 Appendices

9.1 Appendix 1: Correlation charts for the field campaign February 23, 2019 - March 30, 2020

The charts show :

- The distribution of each variable is on the diagonal.
- On the bottom of the diagonal : the bivariate scatter plots with a fitted line
- On the top of the diagonal : the value of the correlation plus the significance level as stars
- Each significance level is associated to a symbol : p-values(0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols("***", "**", "*", ".", " ")

9.1.1 Alphasense B43F NO_2 sensor

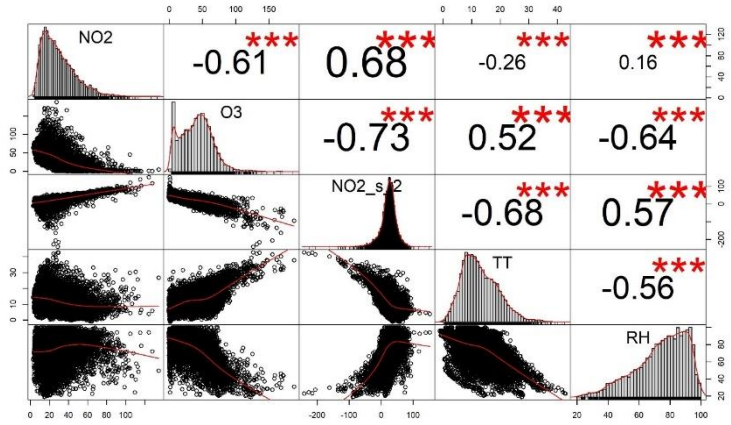


Figure 137: Correlation chart of Alphasense B43F NO_2 sensor VQH0. R = pearson correlation coefficient

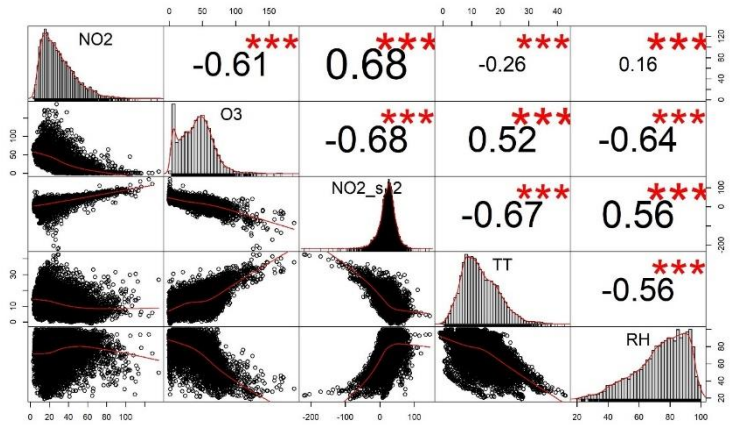


Figure 138: Correlation chart of Alphasense B43F NO_2 sensor VQH1. R = pearson correlation coefficient

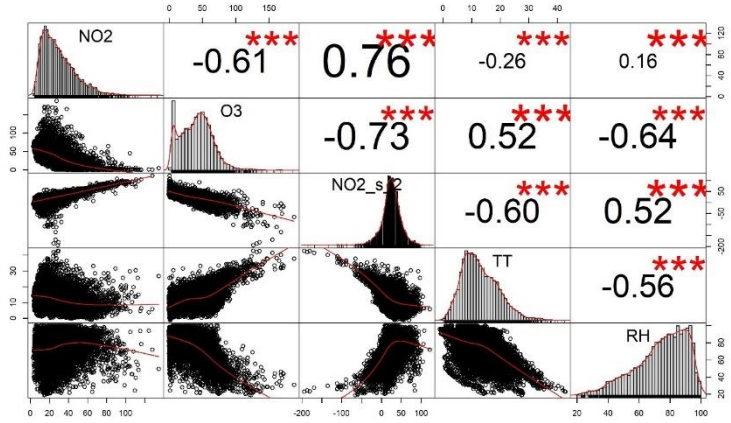


Figure 139: Correlation chart of Alphasense B43F NO_2 sensor VQH2. R = pearson correlation coefficient

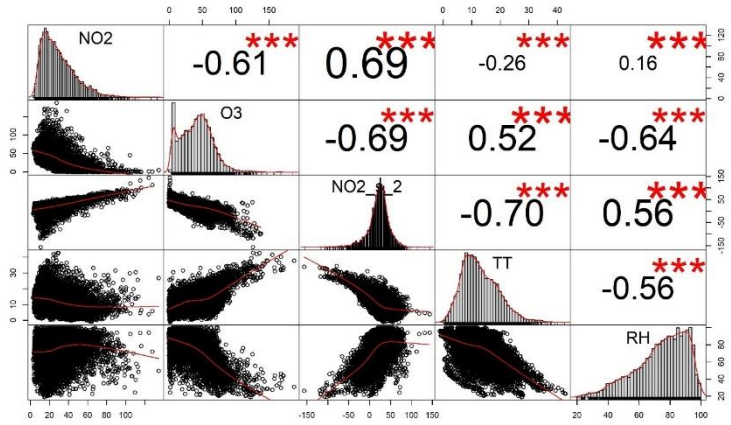


Figure 140: Correlation chart of Alphasense B43F NO_2 sensor VQH5. R = pearson correlation coefficient

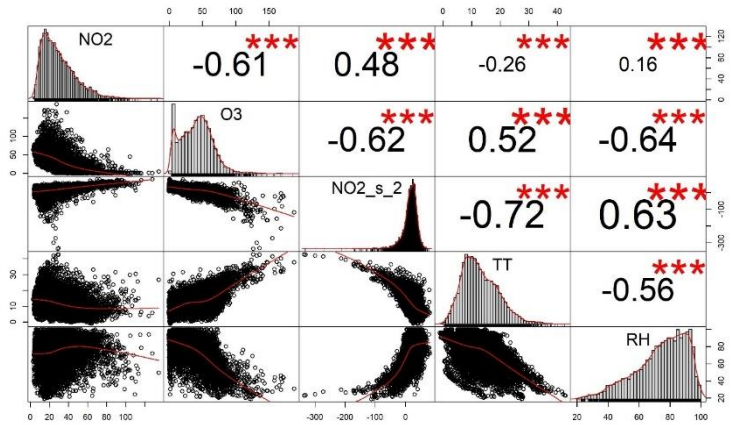


Figure 141: Correlation chart of Alphasense B43F NO_2 sensor VQH6. R = pearson correlation coefficient

9.1.2 Citytech 3E50 NO_2 sensor

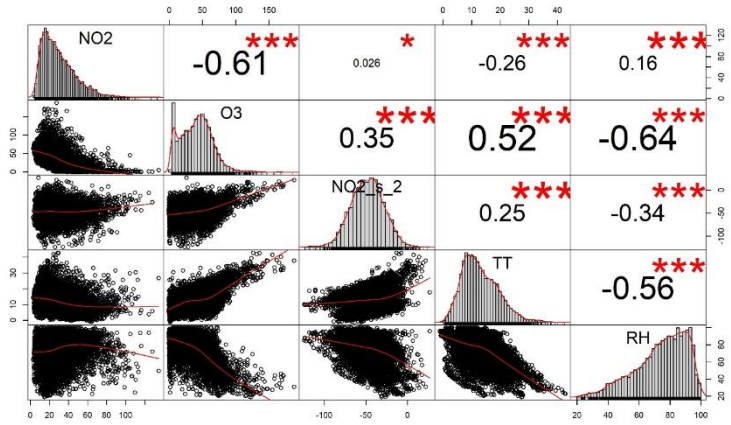


Figure 142: Correlation chart of Citytech 3E50 NO_2 sensor VQI2. R = pearson correlation coefficient

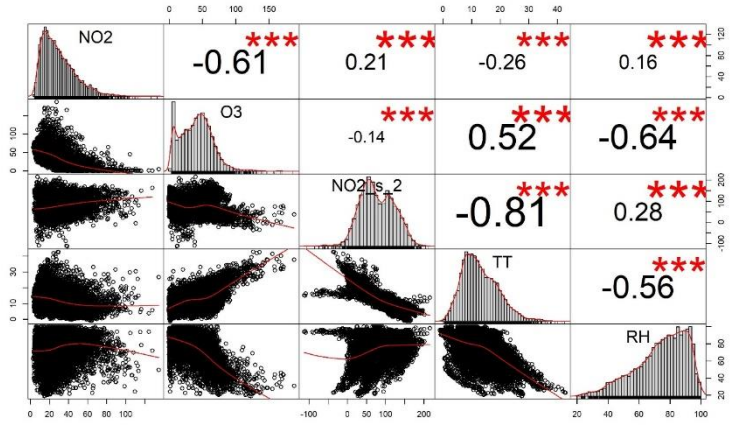


Figure 143: Correlation chart of Citytech 3E50 NO_2 sensor VQI3. R = pearson correlation coefficient

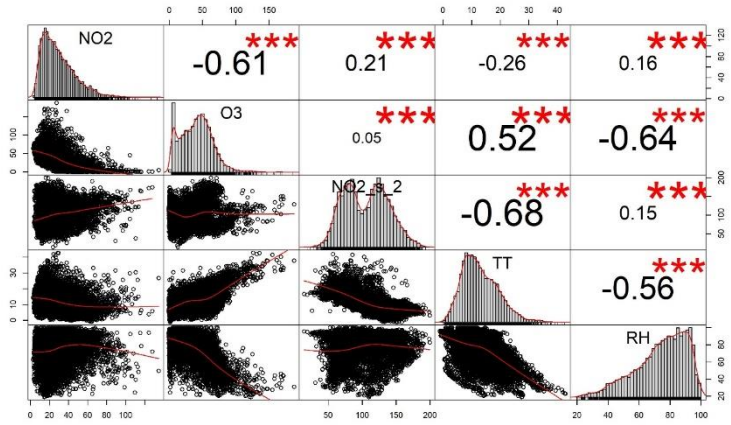


Figure 144: Correlation chart of Citytech 3E50 NO_2 sensor VQI5. R = pearson correlation coefficient

9.1.3 Membrapor C1 NO_2 sensor

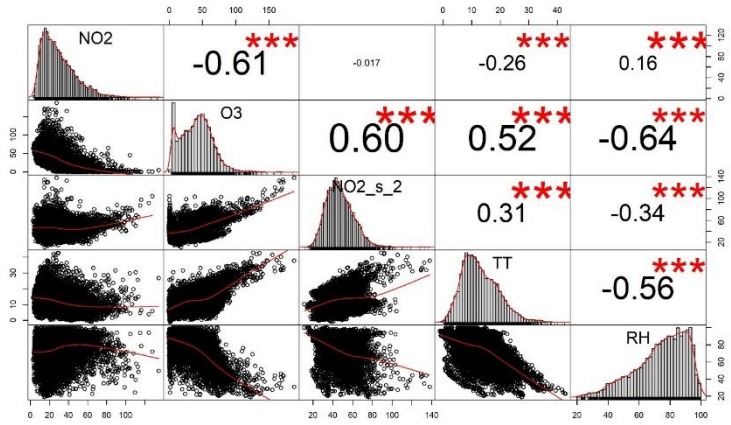


Figure 145: Correlation chart of Membrapor C1 NO_2 sensor VQK1. R = pearson correlation coefficient

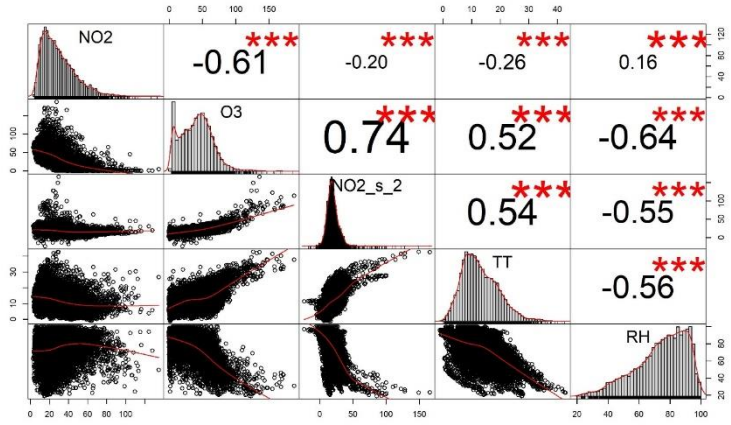


Figure 146: Correlation chart of Membrapor C1 NO_2 sensor VQK2. R = pearson correlation coefficient

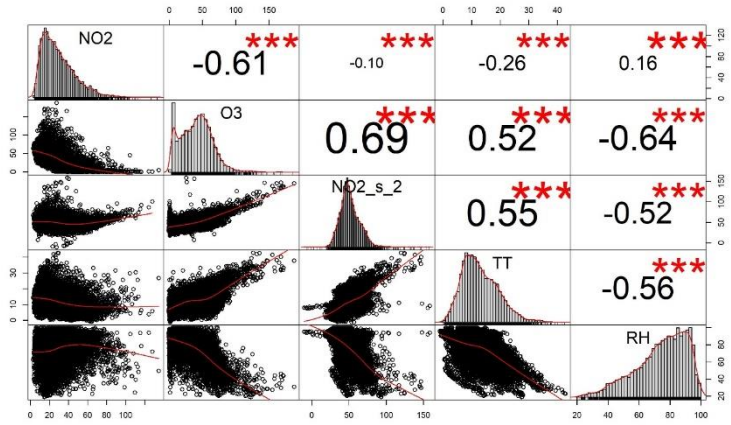


Figure 147: Correlation chart of Membrapor C1 NO_2 sensor VQK3. R = pearson correlation coefficient

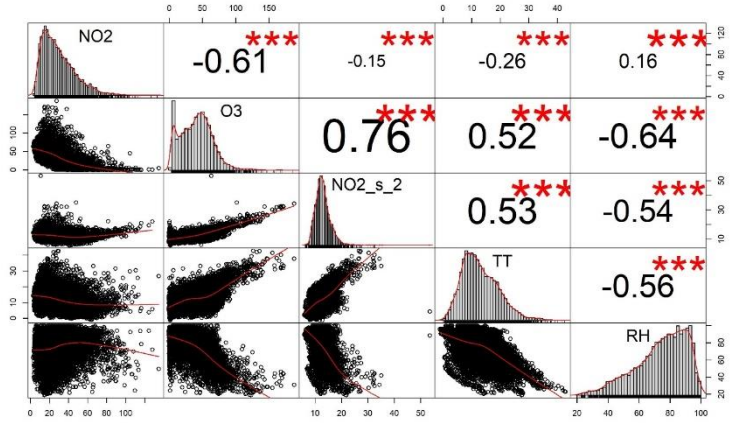


Figure 148: Correlation chart of Membrapor C1 NO_2 sensor VQK4. R = pearson correlation coefficient

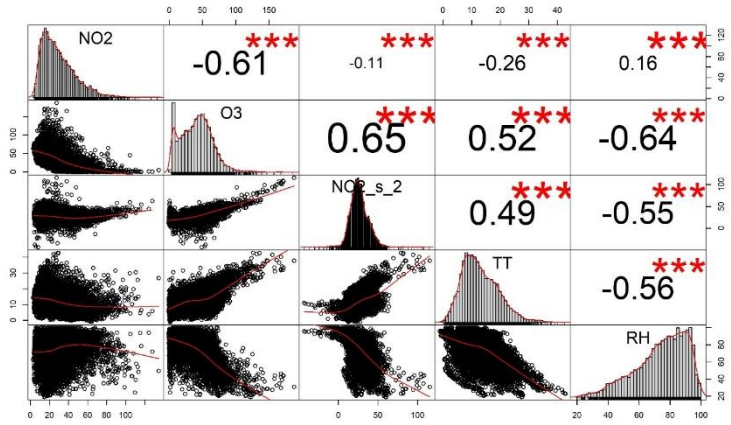


Figure 149: Correlation chart of Membrapor C1 NO_2 sensor VQK5. R = pearson correlation coefficient

9.1.4 Membrapor C20 NO_2 sensor

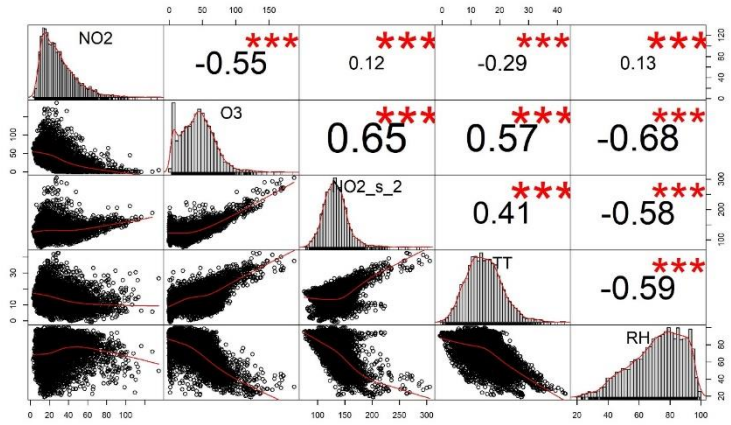


Figure 150: Correlation chart of Membrapor C20 NO_2 sensor VQL1. R = pearson correlation coefficient

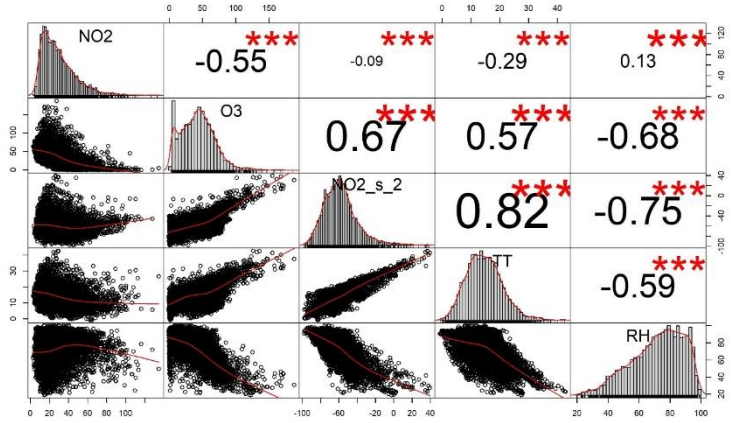


Figure 151: Correlation chart of Membrapor C20 NO_2 sensor VQL2. R = pearson correlation coefficient

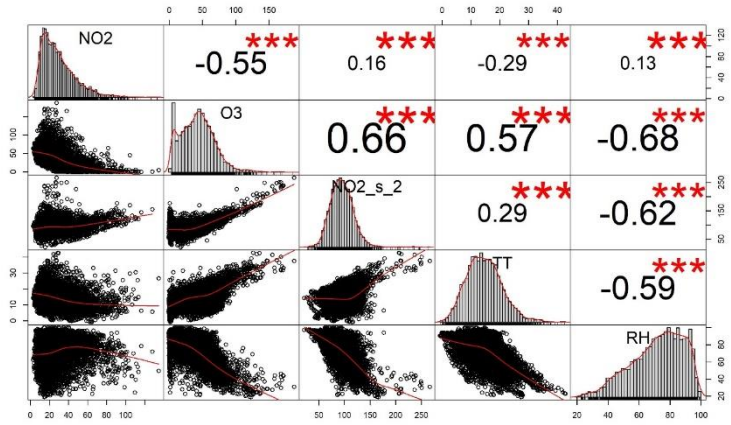


Figure 152: Correlation chart of Membrapor C20 NO_2 sensor VQL3. R = pearson correlation coefficient

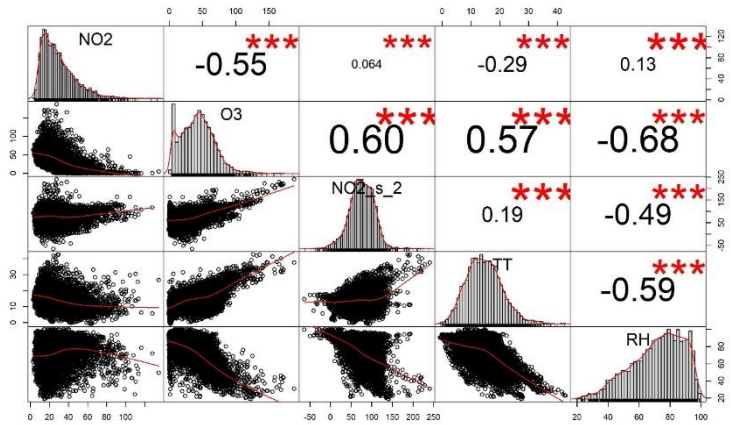


Figure 153: Correlation chart of Membrapor C20 NO_2 sensor VQL4. R = pearson correlation coefficient

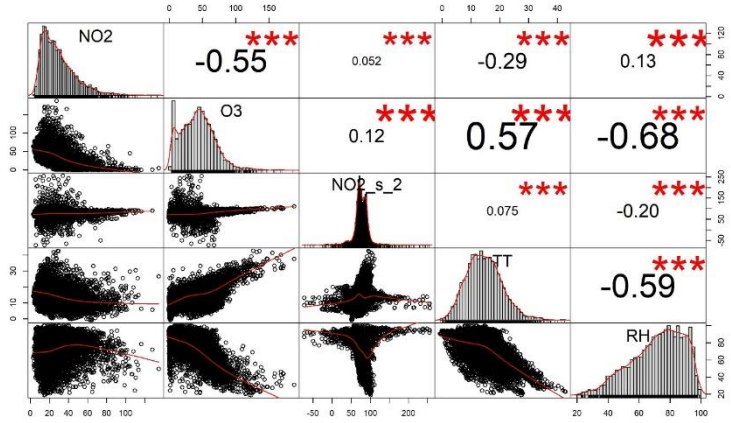


Figure 154: Correlation chart of Membrapor C20 NO_2 sensor VQL5. R = pearson correlation coefficient

9.1.5 Envea Cairclip NO_2 sensor

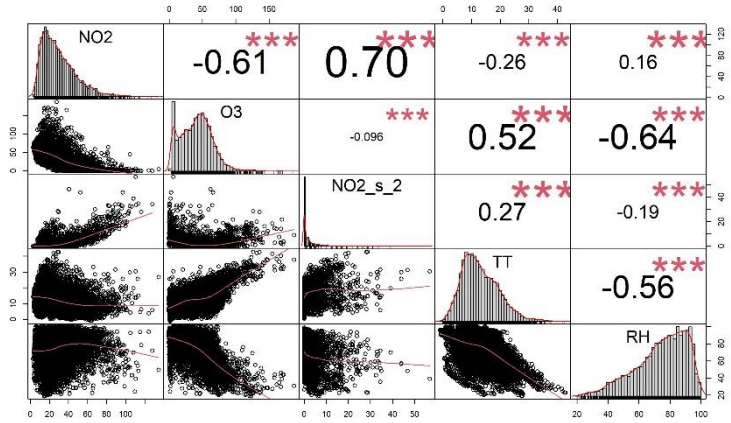


Figure 155: Correlation chart of Envea Cairclip NO_2 sensor VQS1. R = pearson correlation coefficient

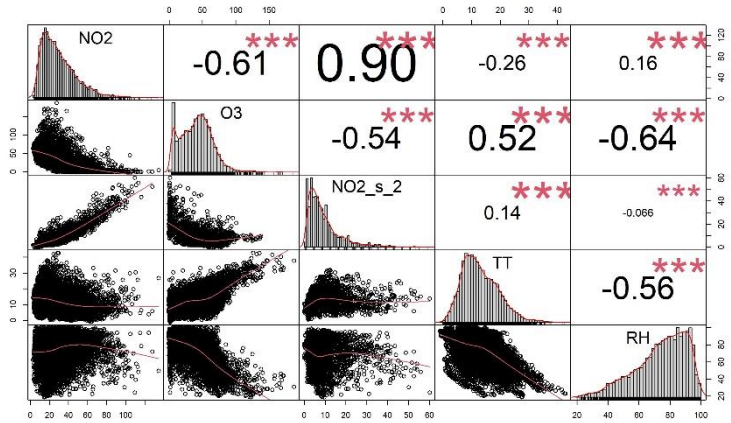


Figure 156: Correlation chart of Envea Cairclip NO_2 sensor VQS2. R = pearson correlation coefficient

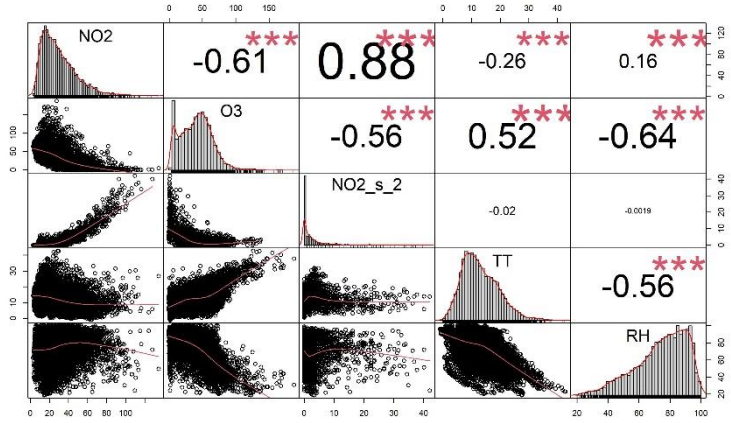


Figure 157: Correlation chart of Envea Cairclip NO_2 sensor VQS3. R = pearson correlation coefficient

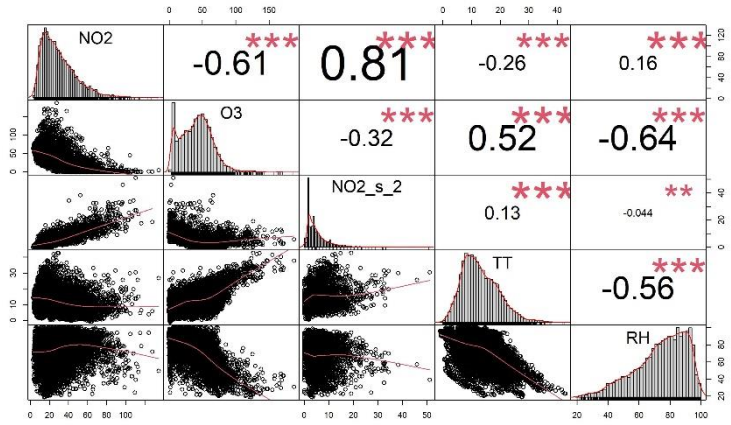


Figure 158: Correlation chart of Envea Cairclip NO_2 sensor VQS4. R = pearson correlation coefficient

9.2 Appendix 2: Calibration parameters from laboratory study

Based on the sensor data of the ramping experiment during the laboratory study, a linear regression function against the reference instrument was calculated.

The table 56 below gives the parameters of this calibration function for the different sensors. The parameters of the Citytech 3E50 are not included due to the fact that during the laboratory study, these sensors were not oriented according to the supplied manual.

VQL2, VQL5 and VQS4 were tested in the laboratory, but showed deviations from the other sensors and were therefore not included in the evaluation of the laboratory testing. VQL1 was not included in the laboratory study.

During the field campaign a linear calibration function was established based on the data from February 23, 2019 - March 31, 2019.

For some the sensor types Membrapor C1 and Membrapor C20 there is almost no correlation ($R^2 < 0.1$) between the uncalibrated sensor data and the reference NO_2 data. For these sensor types the field calibration parameters are not calculated.

The calibration parameters calculated during the laboratory study and the field test are quite different. For the sensor type Envea Cairclip we see no relation between the calibration parameters of the laboratory study and the field test. For the sensor type Alphasense B43F there seems to be some relation : higher slopes during the field campaign along with higher slopes during the laboratory study and less negative intercepts during the field campaign when higher intercepts during the laboratory study were calculated.

Table 57 gives some performance characteristics of the uncalibrated sensor data (*NO2_s_2*) and of the data calibrated with the calibration parameters established during the laboratory study (*NO2_s_lab2*).

Application of the lab calibration parameters does not improve the sensor data. For the sensor type Alphasense B43F, the mean biases for some sensors become more negative, the between sensor uncertainty and the expanded uncertainty at the limit increases. For the sensor type Envea Cairclip the same observations can be made for the mean biases and between sensor uncertainty, with a high negative bias for sensor VQS4. The expanded uncertainty at the limit values increases for some sensors.

This is not surprising, since e.g. temperature, relative humidity and O_3 are known to have an effect on NO_2 sensors. The conditions during the laboratory test with constant temperature and relative humidity and the absence of O_3 are quite different from the conditions during the field test. Different sensors of one sensor type also seem to react differently to variations in temperature, relative humidity and O_3.

Table 55: Calibration parameters based on the laboratory study and field campaign

	Laboratory study		Field campaign	
sensor_internal_id	slope	Intercept (µg/m³)	slope	Intercept (µg/m³)
Alpahsense B43 F				
VQH0	0.80	3.2	1.10	-14.1
VQH1	0.84	1.3	1.13	-17.8
VQH2	0.81	16.3	1.07	-9.8
VQH5	0.82	-4.9	1.08	-15.2
VQH6	0.78	5.9	0.84	-12.7
Membrapor C1				
VQK1	0.62	15.6		
VQK2	0.47	1.3		
VQK3	0.60	28.4		
VQK4	0.14	7.4		
VQK5	0.56	4.9		
Membrapor C20				
VQL1	-	-		
VQL2	0.21	-48.1		
VQL3	0.92	7.2		
VQL4	0.83	10.0		
VQL5	0.20	58.4		
Envea Cairclip				
VQS1	0.73	-2.0	0.21	-2.96
VQS2	0.79	10.7	0.43	-3.49
VQS3	0.71	-8.1	0.27	-5.02
VQS4	0.18	13.1	0.23	-0.76

Table 56: Descriptive parameters of the uncalibrated sensor data (NO2_s_2) and of the sensor data calibrated with the calibration parameters established during the laboratory study (NO2_S_lab2). Mean bias, R^2, u_{bs} (between sampler uncertainty) and W (expanded uncertainty) at 200 µg/m³ on hourly values; W (expanded uncertainty) at 40 µg/m³ on daily values.

	ID	n	mean bias (µg/m³)	R^2	W (%) hourly at 200 µg/m³	W (%) daily at 40 µg/m³	u_{bs} (µg/m³)	u_{bs} (%)
Alpahsense B43 F								
NO2_s_2	VQH0	7743	-6.08	0.46	108.57	83.15		
NO2_s_2	VQH1	7953	-7.30	0.46	99.01	82.00		
NO2_s_2	VQH2	6744	-5.38	0.58	75.56	57.68		
NO2_s_2	VQH5	6869	-9.53	0.47	88.76	84.76		
NO2_s_2	VQH6	7312	-13.50	0.23	183.26	150.75		
NO2_s_2	all sensors	36621					19.38	90.61
NO2_s_lab2	VQH0	7743	-4.07	0.46	210.18	119.99		
NO2_s_lab2	VQH1	7953	-4.81	0.46	173.00	106.8		
NO2_s_lab2	VQH2	6744	-19.85	0.58	136.55	98.86		
NO2_s_lab2	VQH5	6869	1.08	0.47	181.57	120.02		
NO2_s_lab2	VQH6	7312	-16.52	0.23	357.08	250.97		
NO2_s_lab2	all sensors	36621					24.47	116.02
Envea Cairclip								
NO2_s_2	VQS1	4070	-24.91	0.48	161.82	175.36		
NO2_s_2	VQS2	2623	-21.20	0.82	118.00	133.70		
NO2_s_2	VQS3	2491	-27.71	0.77	151.42	172.74		
NO2_s_2	VQS4	4150	-22.42	0.66	155.73	160.81		
NO2_s_2	all sensors	13329					5.17	101.77
NO2_s_lab2	VQS1	4070	-21.16	0.48	143.29	152.45		
NO2_s_lab2	VQS2	2623	-32.16	0.82	108.31	183.41		
NO2_s_lab2	VQS3	2491	-14.96	0.77	119.12	104.70		
NO2_s_lab2	VQS4	4150	-69.96	0.66	44.38	329.85		
NO2_s_lab2	all sensors	13334					27.6	-329.6