Evaluating MODULAIR gas measurements against EPA's Air Sensor Performance Targets

This document summarizes an evaluation performed by QuantAQ to document how MODULAIR gas measurements perform relative to EPA's Air Sensor Performance targets.

The US Environmental Protection Agency (US EPA) released Air Sensor Performance Targets for gas sensors across two reports in 2021 and 2023[1,2]. Here, we present a meta-analysis of MODULAIR performance using NSIM (Non-regulatory Supplemental and Informational Monitoring) guidelines and evaluation metrics at locations around the world. This summary document covers QuantAQ's 2024 model release which were rolled out to customers beginning in Q2 of 2024. The MODULAIR meets or exceeds NSIM targets for CO and NO_2 while slightly missing on O_3. NO is included in this report, though there are no EPA NSIM performance targets for NO.

Metric		CO	O_3	NO*	NO_2
Bias	Slope	0.85	1.01	0.92	0.72
	Intercept (ppbv)	25.3	-1.2	0.3	1.8
Linearity	Pearson R^2	0.87	0.91	0.86	0.72
Precision	SD (ppbv)	16.4	3.2	1.8	1.3
	Coef. of Variation (%)	5.8	10.7	39.9	17.5
Error	MAE (ppbv)	65.0	4.0	3.0	3.0
	RMSE (ppbv)	84.6	5.2	5.1	4.3

Table 1. US EPA NSIM target summary table. All metrics shown in black text for CO, O_3, and NO_2 meet or exceed expected quality standards set by EPA. *NO is not a criteria pollutant and NSIM standards are not set by EPA; however, we have listed the evaluation metrics using the same guidelines. Values shown in red text did not meet EPA NSIM standards; only the RMSE for O_3 currently does not meet NSIM standards (target is < 5 ppb for O_3).

Data and Methodology

Data used in this evaluation were gathered from long-running co-location studies from the United States and the United Kingdom. All data used are from previously unseen MODULAIR sensors and locations that represent various environments that differ in climate and pollutant ranges. All reference data are from US EPA FEM-grade reference monitors, though the exact make and model vary site-to-site. A summary of the test sites and data used in this evaluation can be found in Table 2.

	Test Sites / Devices / Number of Records			
Climate	CO	O_3	NO	NO_2
US Northeast	2 / 6 / 15.5k	2 / 5 / 11.8k	2 / 6 / 15.5k	3 / 8 / 19.6k
US Northwest	1 / 1 / 865	1 / 1 / 886	1 / 1 / 865	1 / 1 / 865
UK Southwest	-	1 / 2 / 730	2 / 2 / 1378	2 / 2 / 1378

Table 2. Data locations and availability. Data locations are described by country and region to provide context around environmental conditions. The number of records represents the number of hourly data records used in the evaluation from that location.

The devices used in this evaluation followed the same calibration process used across all QuantAQ products. Before shipment, each MODULAIR undergoes a laboratory-based calibration where sensors are placed in our environmental chamber and undergo a multi-point calibration using known concentrations of target gases. Concentrations are verified using a suite of Teledyne gas analyzers (T300, T200U, T100, T400) which are calibrated and maintained according to the manufacturer's specifications. Sensor calibration parameters are recorded and fed into gas-specific global models that incorporate knowledge about how specific electrochemical sensors respond to different environments and cross-sensitivities.

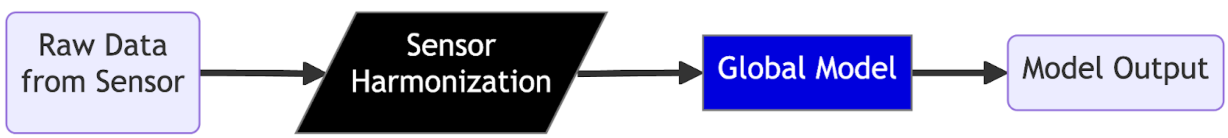

Figure 1. QuantAQ gas sensors undergo a multi-step process to produce final concentration readings.

Model Details

For each target analyte, we provide a brief description and site-specific evaluations. Marker color indicates location and marker shape indicates the broader climate region. The NSIM evaluation metrics are calculated for each sensor at each site and then aggregated. We aggregate by site rather by individual sensor; in other words, if location 1 has ten sensors and location 2 has 1 sensor, the sensors at location 1 count 1/10 as much in the overall aggregation as the sensor at location 2. We have chosen this approach as we believe it is more representative of what you can expect to see if deploying your sensor in a completely new location.

Carbon Monoxide (CO)

Our CO model uses a Multi-variate Linear Regression which is effective due to the strong linearity of our electrochemical sensor's response to CO.

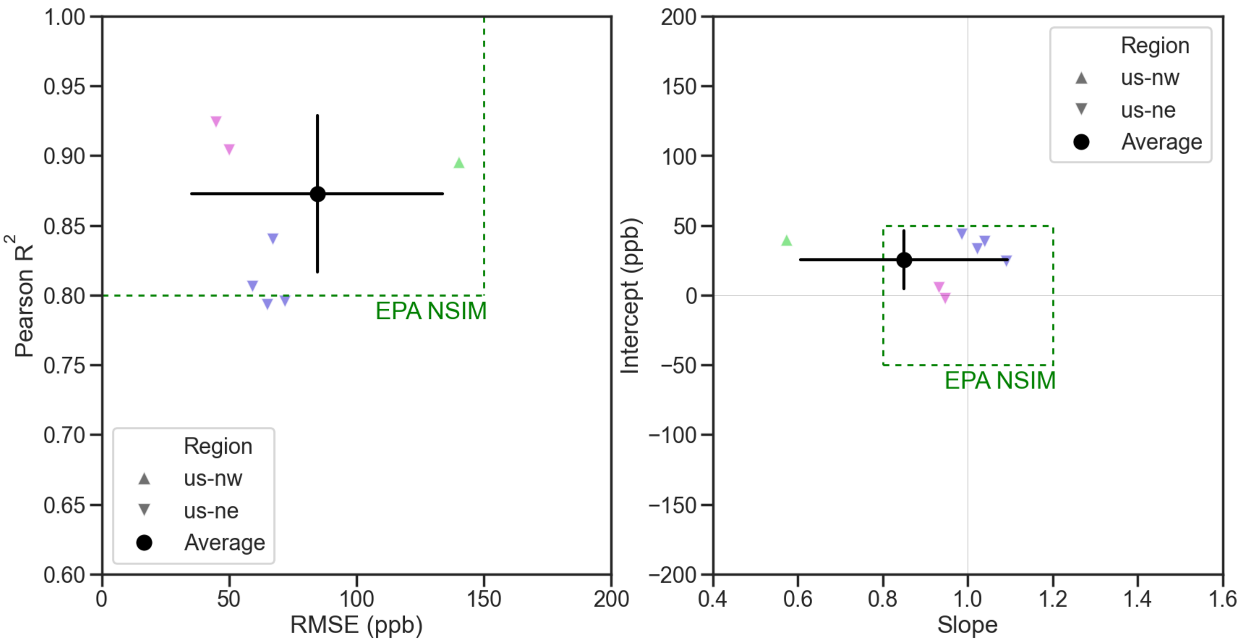

Figure 2. CO performance against EPA NSIM guidelines. The subplot on the left shows results for linearity and error and the subplot on the right shows results for bias. Bounding boxes, shown in green, indicate the range that meets or exceeds NSIM guidelines.

Below, we list the US EPA NSIM guidelines and results for CO.

		NSIM Target	Reported	Result
Precision	Standard Dev. (ppbv)	≤ 20	16.4	PASS
	Coef. of Variation (%)	≤ 30	5.8	PASS
Bias	Slope	1.0 ± 0.2	0.83	PASS
	Intercept (ppbv)	-50 ≤ b ≤ 50	30.5	PASS
Linearity	Pearson R^2	≥ 0.80	0.86	PASS
Error	RMSE (ppbv)	≤ 150	90.8	PASS

Our CO *sensor meets or exceeds all EPA NSIM guidelines*.

Ozone (O_3)

Our O_3 model is based on a feed-forward neural network that excels at modeling dependencies between interacting features and handling non-linear behavior. Neural networks can learn complex functions of their inputs, broadly inspired by the design of biological neural networks.

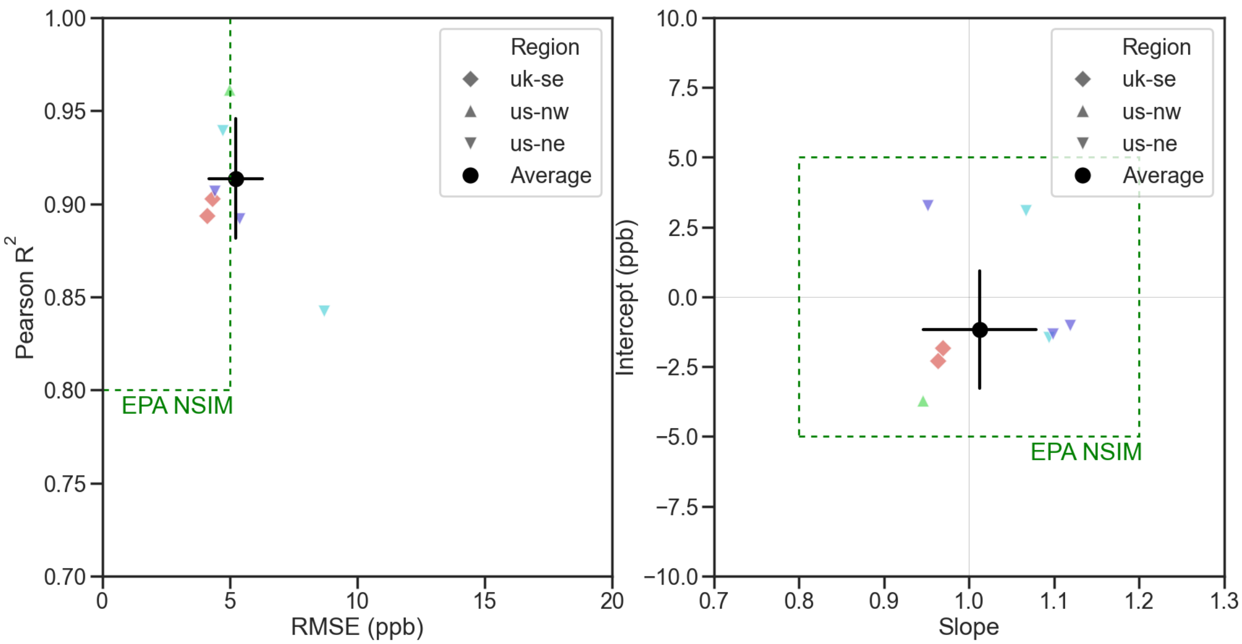

Figure 3. O3 performance against EPA NSIM guidelines. The subplot on the left shows results for linearity and error and the subplot on the right shows results for bias. Bounding boxes, shown in green, indicate the range that meets or exceeds NSIM guidelines.

Below, we list the US EPA NSIM guidelines and results for O_3.

		NSIM Target	Reported	Result
Precision	Standard Dev. (ppbv)	≤ 5	3.2	PASS
	Coef. of Variation (%)	≤ 30	10.7	PASS
Bias	Slope	1.0 ± 0.2	1.02	PASS
	Intercept (ppbv)	-5 ≤ b ≤ 5	-1.4	PASS
Linearity	Pearson R^2	≥ 0.80	0.92	PASS
Error	RMSE (ppbv)	≤ 5	5.2	FAIL

Our O_3 sensor ***does not meet or exceed EPA NSIM guidelines*** due to the RMSE failing to meet the threshold set by EPA, largely due to results found at a single location.

Nitric Oxide (NO)

Our NO model uses a hybrid regression algorithm that combines a linear model with a gradient-boosted random forest (GBRF) regression model, using a physics-inspired voting process in a stacked regression to account for meteorological differences in sensor response[3,4]. The linear model handles cases where the underlying data are strongly linear and the GBRF is capable of learning highly non-linear input-output behaviors, iteratively adding decision trees to address errors from earlier iterations.

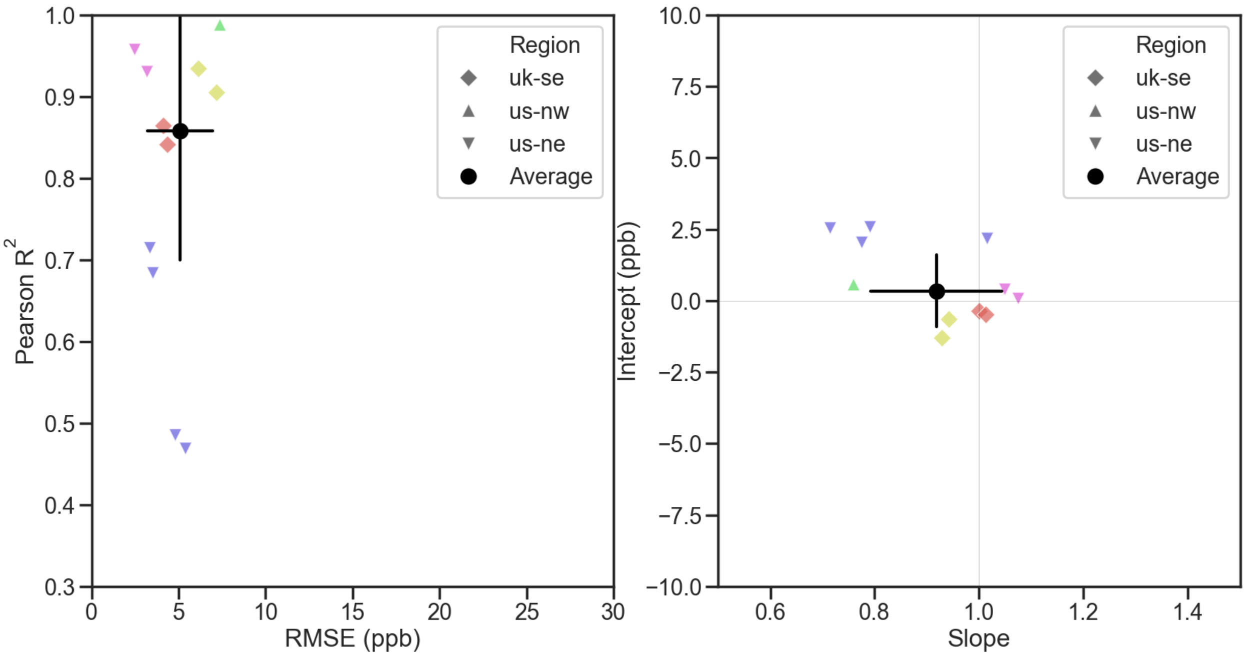

Figure 4. NO performance using the same methodology used for other gases and NSIM guidelines. Note, there are no EPA NSIM guidelines for NO. The subplot on the left shows results for linearity and error and the subplot on the right shows results for bias. There are no bounding boxes for NO as there are no NSIM guidelines for NO.

Below, we list the results for NO, though there are no official NSIM guidelines.

		NSIM Target	Reported	Result
Precision	Standard Dev. (ppbv)	NA	1.8	
	Coef. of Variation (%)	NA	39.9	
Bias	Slope	NA	0.92	
	Intercept (ppbv)	NA	0.4	
Linearity	Pearson R^2	NA	0.86	
Error	RMSE (ppbv)	NA	5.4	

Nitrogen Dioxide (NO_2)

Like NO, our NO_2 model uses a hybrid regression algorithm that combines a linear model with a gradient-boosted random forest (GBRF) regression model.

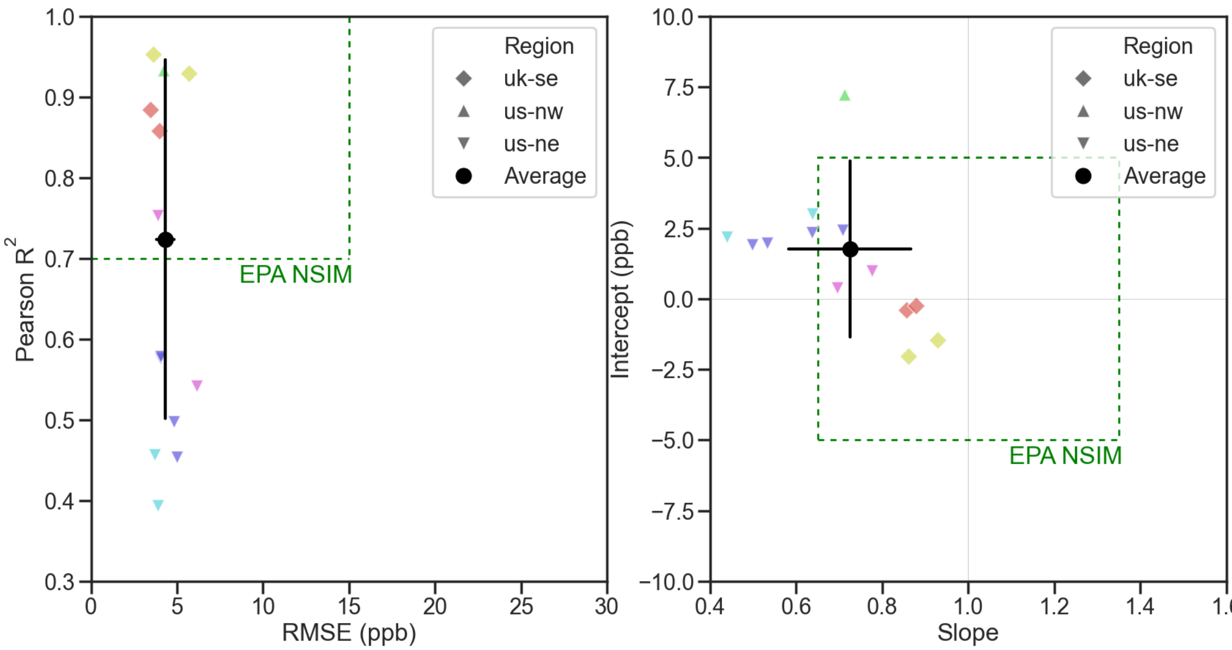

Figure 5. NO_2 performance against US EPA NSIM guidelines. The subplot on the left shows results for linearity and error and the subplot on the right shows results for bias. Bounding boxes, shown in green, indicate the range that meets or exceeds NSIM guidelines.

Below, we list the US EPA NSIM guidelines and results for NO_2.

		NSIM Target	Reported	Result
Precision	Standard Dev. (ppbv)	≤ 5	1.3	PASS
	Coef. of Variation (%)	≤ 30	17.5	PASS
Bias	Slope	1.0 ± 0.35	0.72	PASS
	Intercept (ppbv)	-5 ≤ b ≤ 5	1.8	PASS
Linearity	Pearson R^2	≥ 0.70	0.72	PASS
Error	RMSE (ppbv)	≤ 15	4.3	PASS

Our NO_2 *sensor meets or exceeds all EPA NSIM guidelines.*

Citing this document

If you would like to reference this document, please use the citation format listed below. For more information, please visit the direct link on Zenodo.

David McClosky & David H. Hagan. (2024). Evaluating MODULAIR gas measurements against EPA Air Sensor Performance Targets. (2024.04). https://doi.org/ 10.5281/zenodo.11086919

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(2) Duvall, R.; Clements, A.; Barkjohn, K.; Kumar, M.; Greene, T.; Dye, T.; Papapostolou, V.; Mui, W.; Kuang, M. NO2, CO, and SO2 Supplement to the 2021 Report on Performance Testing Protocols, Metrics, and Target Values for Ozone Air Sensors; EPA/600/R-23/146; U.S. Environmental Protection Agency, 2024. https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=360578&Lab=CEMM (accessed 2024-04-28).

(3) Hagan, D. H.; Isaacman-VanWertz, G.; Franklin, J. P.; Wallace, L. M. M.; Kocar, B. D.; Heald, C. L.; Kroll, J. H. Calibration and Assessment of Electrochemical Air Quality Sensors by Co-Location with Regulatory-Grade Instruments. Atmos Meas Tech **2018**, 11 (1), 315–328. https://doi.org/10.5194/amt-11-315-2018.

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Changelog

2024.04.29	This is the first release of QAN 004.