Evaluating the Performance of the MODULAIR-PM Particulate Matter Sensor in Jurupa Valley, CA

This document covers the performance of the MODULAIR-PM Dual Detection particulate matter sensor used in the MODULAIR and MODULAIR-PM products.

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Introduction

The MODULAIR-PM particulate matter sensor uses a patent-pending Dual Detection sensing approach that fuses nephelometry with single-particle scattering to count and size particles up to 40 µm in diameter[1]. A complete description of the operating principle, algorithm, and data corrections can be found in "QAN-001 Introduction to the MODULAIR-PM"[1]. The MODULAIR™ and MODULAIR™-PM use the same particle sensing apparatus and the results in this document apply to both devices. This document describes results from data collected during a quality evaluation performed by the South Coast Air Quality Management District (South Coast AQMD) in 2021 as part of the AQ-SPEC program. *The South Coast AQMD has not reviewed or endorsed this work. The original report produced by South Coast AQMD can be found on* *their website*.

The original report released by South Coast AQMD uses an earlier version of QuantAQ's algorithms used to compute PM_1, $PM_{2.5}$, and PM_{10} values from raw data. The data and results shown herein include re-analyzed data using the current algorithm (v3.0). No data from this co-location was used in the development or training of the algorithm.

Methods

Three MODULAIR-PM particulate matter sensors (MOD-PM-00055, MOD-PM-00059, and MOD-PM-00069) were co-located with two US EPA Federal Equivalent Method (FEM) particulate matter analyzers (Teledyne T640, GRIMM EDM 180) between September 10th, 2021 and November 5th, 2021 at the South Coast AQMD Rubidoux ambient air quality monitoring station. Data were recorded at 1-minute resolution for all instruments. According to South Coast AQMD, "basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, and invalid data points were eliminated from data dataset)".

Reference data from both analyzers (GRIMM, T640) were provided by South Coast AQMD and are otherwise un-modified. Data from the MODULAIR-PM sensors have been re-evaluated using the most current data processing algorithm; however, the raw data is un-modified. We present results according to the requirements of the U.S. Environmental Protection Agency's Air Sensor Performance Targets guidebook for Non-regulatory, Supplemental, and Informational Monitoring (NSIM) measurements[2,3].

Ambient Data

Data were collected using two different FEM analyzers throughout the measurement period. PM values for both analyzers are shown in Figure 1 as distributions for PM_1, $PM_{2.5}$, and PM_{10}. The GRIMM and T640 agree to within 10.1, 7.1, and 8.7 percent of one another for PM_1, $PM_{2.5}$, and PM_{10} respectively. The evaluation period lasted for just under 57 days with a total of 16,415 5-minute periods, 1,368 1-hour periods, and 57 24-hour periods available for comparison.

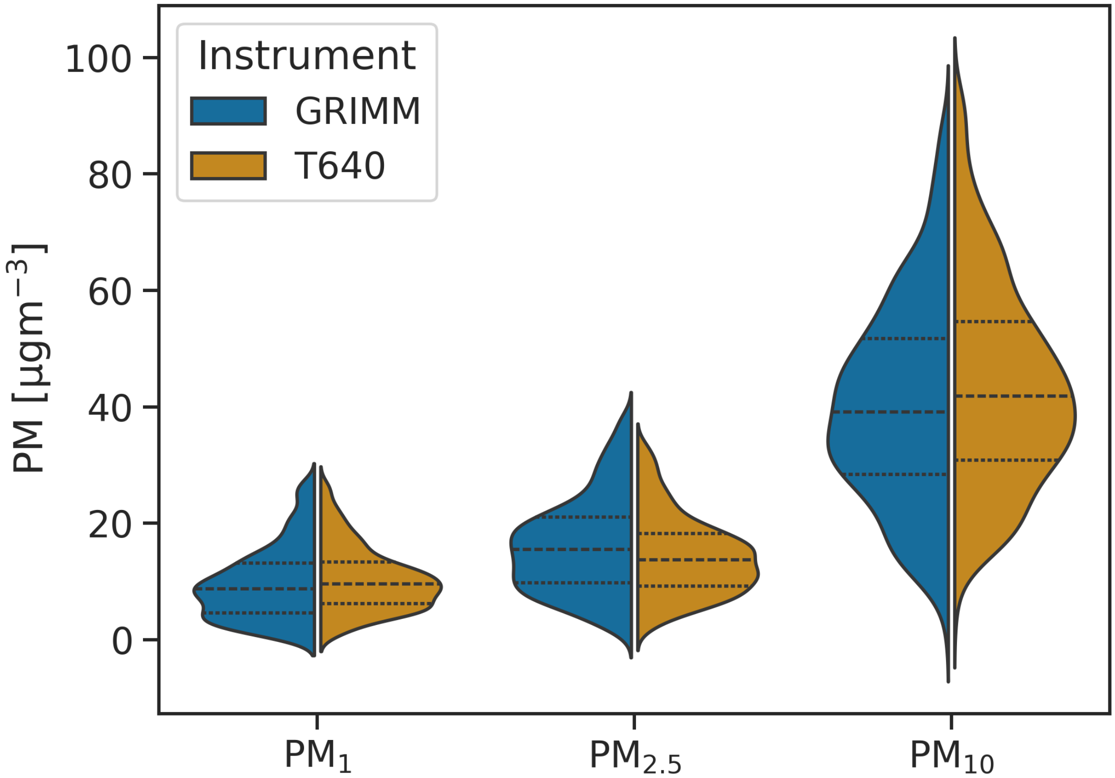

Figure 1. Distributions of PM_1, $PM_{2.5}$, and PM_{10} for both the Teledyne T640 (orange) and GRIMM EDM 180 (blue) are shown throughout the measurement period as hourly averages. Each split violin shows the distribution of hourly measurements taken throughout the measurement period. The mean is shown as the darker, thicker dashed line and the interquartile range is shown as the thinner, lighter dotted line. The GRIMM and T640 generally agree with one another, with differences in the mean measurement of 10.1, 7.1, and 8.7 percent for PM_1, $PM_{2.5}$, and PM_{10} respectively.

The mean, minimum, and maximum values for all three pollutants can be found in Table 1 below.

	PM_1		$PM_{2.5}$		PM_{10}	
	T640	GRIMM	T640	GRIMM	T640	GRIMM
Min. [μgm^{-3}]	0.6	0.3	1.4	0.9	3.6	1.2
Mean [μgm^{-3}]	11.8	10.6	15.5	16.6	47.3	43.2
Max [μgm^{-3}]	50.7	43.6	57.4	50.3	374.1	197.9

Table 1. The mean, minimum, and maximum hourly-averaged values for all three pollutants for both instruments are shown.

To properly evaluate the ability of the MODULAIR-PM to measure coarse particles, we calculate the ratio of $PM_{2.5}$ to PM_{10}. The EPA NSIM evaluation requires at least 1-hour where PM_{10}:$PM_{2.5}$ < 0.4, indicating the presence of coarse aerosol. Figure 2 shows the cumulative distribution curves for the $PM_{2.5}$:PM_{10} and PM_1:$PM_{2.5}$ ratios, which shows there was substantial variation in the underlying particle size distribution throughout the evaluation period. There were a total of 623 hours (55%) where the $PM_{2.5}$:PM_{10} ratio was less than 0.4. Throughout the evaluation period, there were 20 days in which $PM_{2.5}$ exceeded 18 μgm^{-3} and 48 days in which PM_{10} exceeded 30 $\mu gm^{-3.}$

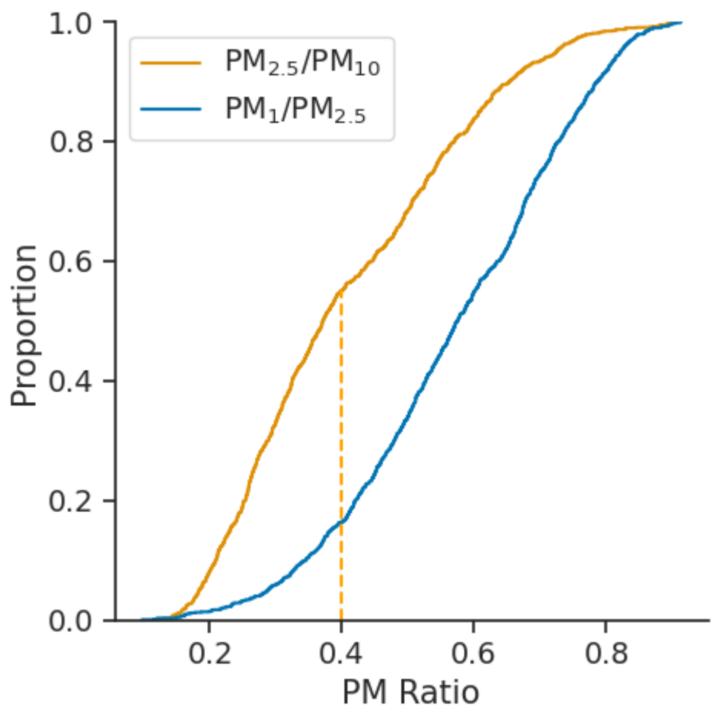

Figure 2. The cumulative distribution of PM ratios shows the $PM_{2.5}$:PM_{10} ratio was at or below 0.4 for 55% of the total hours (n = 623) which exceeds the NSIM requirement of 1 hour throughout the measurement period.

Results

Data Recovery

The uptime for a device is defined as the number of successfully recovered data records divided by the expected number of data records based on the defined data recording interval.

$$Uptime = \frac{\#\ recovered\ data\ records}{\#\ expected\ data\ records}$$

For the evaluation period, we expect 16,415 5-minute data records, 1,368 1-hour data records, and 57 24-hour data records. Table 2 documents the uptime for each device, pollutant, and data recording interval. The uptime for the MODULAIR-PM is described by the mean and standard deviation of the uptime for all three units.

Pollutant		*5-minute*	*60-minute*	*24-hour*
PM_1	**GRIMM EDM 180**	87.0 %	87.2 %	91.2 %
	Teledyne T640	99.9 %	100.0 %	100.0 %
	MODULAIR-PM	99.1 (± 0.0) %	99.3 (± 0.0) %	100.0 (± 0.0) %
$PM_{2.5}$	**GRIMM EDM 180**	87.0 %	87.2 %	91.2 %
	Teledyne T640	99.9 %	100.0 %	100.0 %
	MODULAIR-PM	99.1 (± 0.0) %	99.3 (± 0.0) %	100.0 (± 0.0) %
PM_{10}	**GRIMM EDM 180**	86.9 %	87.2 %	91.2 %
	Teledyne T640	99.9 %	100.0 %	100.0 %
	MODULAIR-PM	99.1 (± 0.0) %	99.3 (± 0.0) %	100.0 (± 0.0) %

Table 2. Uptime for the MODULAIR-PM, T640, and GRIMM analyzers for all three pollutants and all three resampling intervals.

Data recovery for all three MODULAIR-PM units was greater than 99% for all pollutants and data recording intervals.

MODULAIR-PM vs. US EPA FEM

To compute statistics and comparisons for the following section, we use data from the Teledyne T640 as the reference analyzer.

PM_1 Performance Evaluation

The MODULAIR-PM sensors show strong correlations with the corresponding FEM Teledyne T640 data. EPA does not provide NSIM guidance for PM_1 measurements as it is not a criteria pollutant; however, we describe the performance using the same metrics as used for the $PM_{2.5}$ and PM_{10} NSIM guidelines. A summary of overall performance can be found in Table 3.

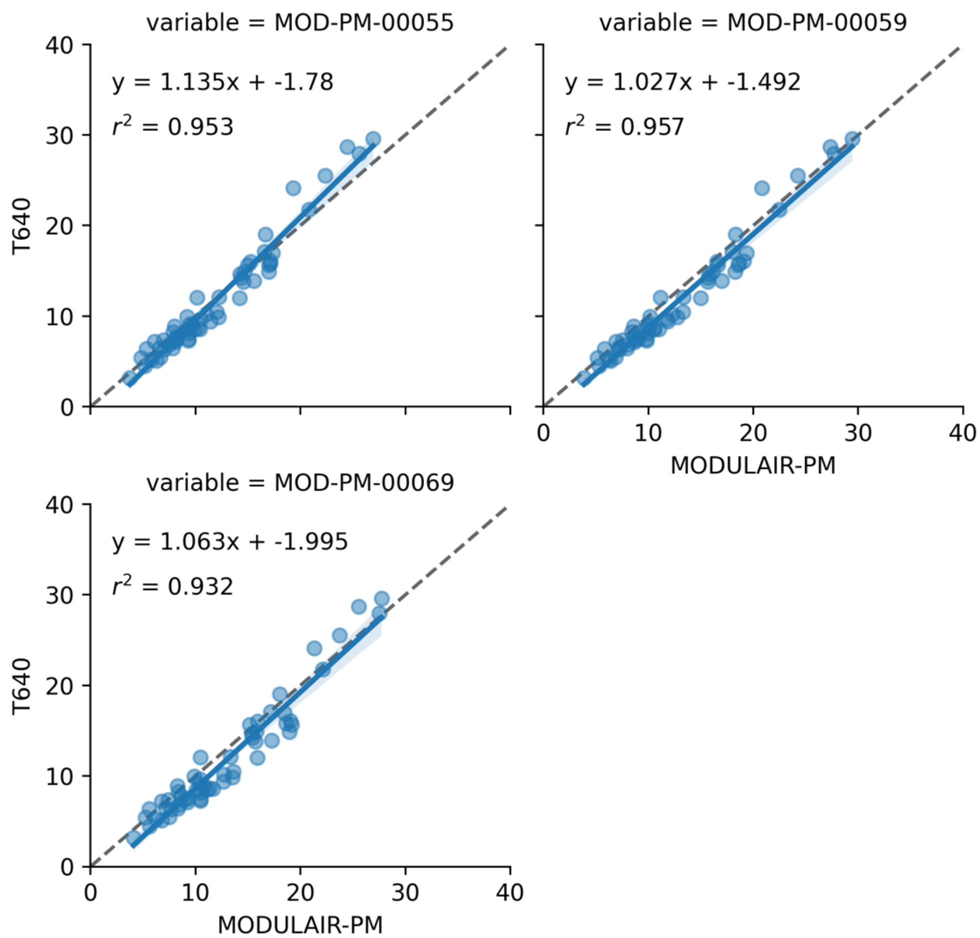

Figure 3. Scatter plots showing the PM_1 performance of three MODULAIR-PM units against the FEM Teledyne T640 are shown as daily averages.

		NSIM Target	*Reported*	*Result*
Precision	Standard Dev.	NA	0.6	NA
	Coef. of Variation (%)	NA	5.2	NA
Bias	Slope	NA	1.08	NA
	Intercept	NA	-1.8	NA
Linearity	Pearson R^2	NA	0.95	NA
Error	Root Mean Squared Error (RMSE)	NA	1.8	NA
	Normalized Root Mean Squared Error (NRMSE)	NA	14.1	NA

Table 3. PM_1 performance summary statistics using NSIM metrics. NSIM targets and results are left blank as there is no official PM_1 NSIM guidance from EPA.

$PM_{2.5}$ Performance Evaluation

The MODULAIR-PM sensors show strong correlation with the corresponding FEM Teledyne T640 data. All metrics meet or exceed the requirements for EPA's NSIM designation. A summary of all statistics can be found in Table 4.

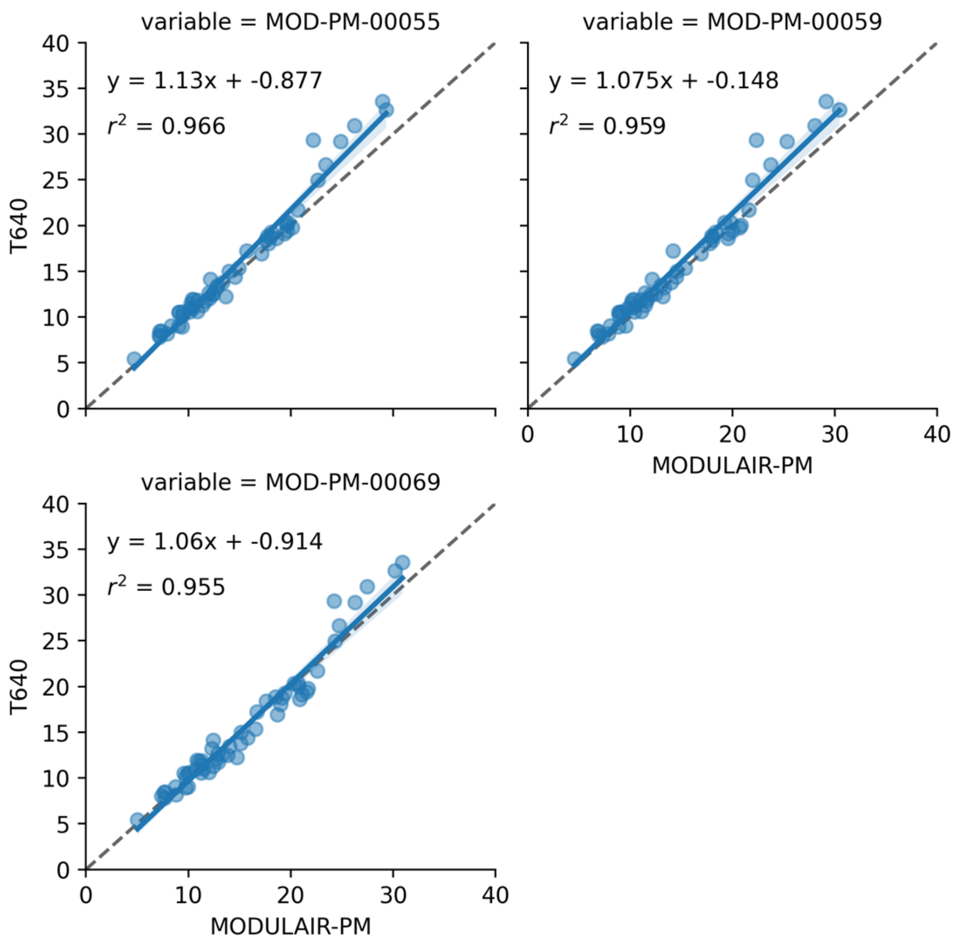

Figure 4. Scatter plots showing the $PM_{2.5}$ performance for three MODULAIR-PM units against the FEM Teledyne T640 are shown as daily averages.

		NSIM Target	Reported	Result
Precision	Standard Dev.	≤ 5 μgm^{-3}	0.6	PASS
	Coef. of Variation (%)	≤ 30 %	4.6	
Bias	Slope	1 ± 0.35	1.09	PASS
	Intercept	-5 ≤ b ≤ 5 μgm^{-3}	-0.6	PASS
Linearity	Pearson R^2	≥ 0.7	0.96	PASS
Error	Root Mean Squared Error (RMSE)	≤ 7 μgm^{-3}	1.6	PASS
	Normalized Root Mean Squared Error (NRMSE)	≤ 30%	11.1	

Table 4. $PM_{2.5}$ performance summary statistics and NSIM evaluation results.

PM_{10} Performance Evaluation

The MODULAIR-PM sensors show strong correlation with the corresponding FEM Teledyne T640 data. All metrics meet or exceed the requirements for EPA's NSIM designation. A summary of all statistics can be found in Table 5.

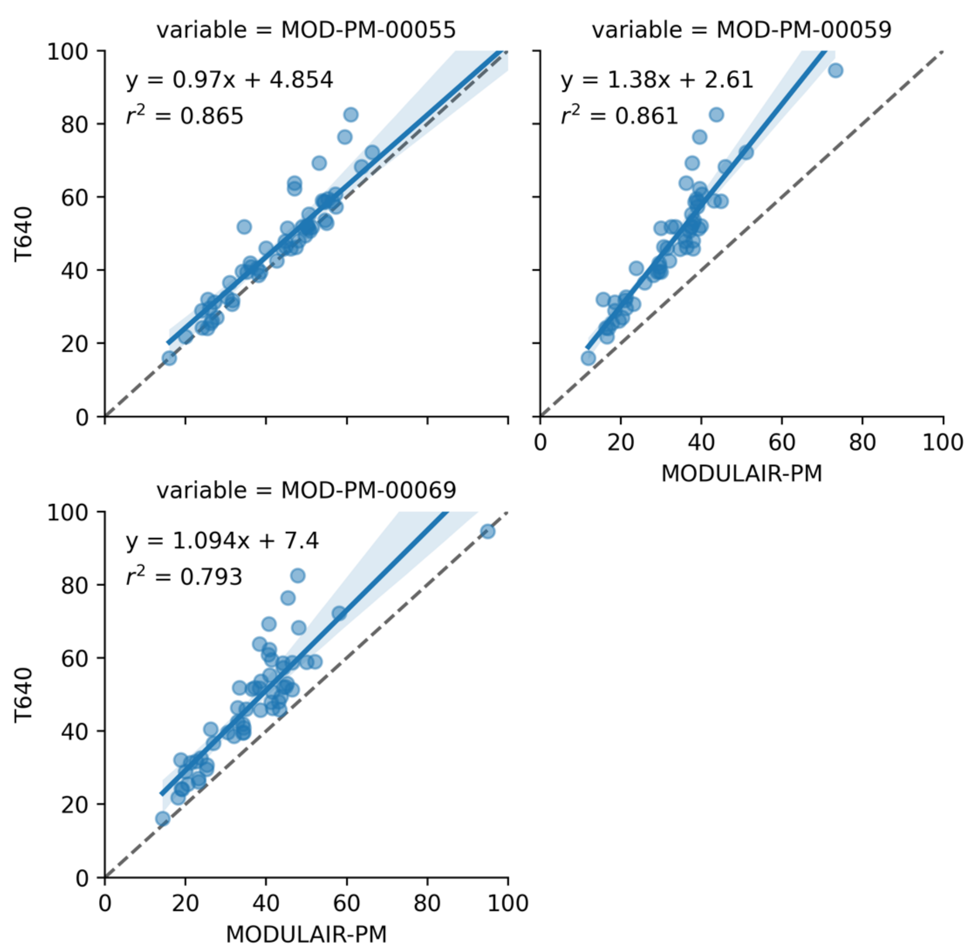

Figure 5. Scatter plots showing the PM_{10} performance for three MODULAIR-PM units against the FEM Teledyne T640 are shown as daily averages.

These values are computed based on daily-averaged data in accordance with the NSIM guidelines.

		NSIM Target	*Reported*	*Result*
Precision	Standard Dev.	≤ 5 μgm^{-3}	17.0	PASS
	Coef. of Variation (%)	≤ 30 %	21.5	
Bias	Slope	1 ± 0.35	1.15	PASS
	Intercept	$-5 \le b \le 5$ μgm^{-3}	4.9	PASS
Linearity	Pearson R^2	≥ 0.7	0.84	PASS
Error	Root Mean Squared Error (RMSE)	≤ 14 μgm^{-3}	12.1	
	Normalized Root Mean Squared Error (NRMSE)	≤ 30%	34.0	PASS

Table 5. PM_{10} performance summary statistics and NSIM evaluation results.

U.S. EPA NSIM Evaluation

PM_1, $PM_{2.5}$, and PM_{10} all showed high precision and excellent agreement with the US EPA FEM analyzers. The devices show high precision for all three pollutants, with a coefficient of variation of 5.2, 4.7, and 16.8% respectively. Additionally, the devices meet NSIM guidelines for bias, linearity, and error. The MODULAIR-PM $PM_{2.5}$ and PM_{10} measurements meet or exceed NSIM guidelines for this location. Importantly, they do so at a measurement location that exhibits a high variance in coarse aerosol loadings which demonstrates the MODULAIR-PM's excellent ability to distinguish between fine and coarse aerosol in a harsh environment over the course of more than 50 days.

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 H. Hagan. (2024). Evaluating the Performance of the MODULAIR-PM Particulate Matter Sensor in Jurupa Valley, CA. (2024.05). https://doi.org/10.5281/zenodo.11200301

References

(1) Hagan, D. H.; Cross, E. S. *(QAN 001) Introduction to the MODULAIR-PM*; 2024.02; Zenodo, 2024. https://zenodo.org/records/10688216 (accessed 2024-02-21).

(2) Duvall, R. A.; Clements, A.; Hagler, G.; Kamal, A.; Kilaru, V. J.; Goodman, L.; Frederick, S.; Barkjohn, K.; VonWald, I.; Greene, D.; Dye, T. *Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors: Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications*; EPA/600/R-20/280; U.S. Environmental Protection Agency: Washington DC, 2021. https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NERL&dirEntryId=277996 (accessed 2023-06-08).

(3) Duvall, R. A.; Clements, A.; Barkjohn, K.; Kumar, M.; Greene, D.; Dye, T.; Papapostolou, V.; Mui, W.; Kuang, M. *PM10 Supplement to the 2021 Report on Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors*; EPA/600/R-23/145; U.S. Environmental Protection Agency: Washington DC, 2023. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=360419&Lab=CEMM (accessed 2024-05-14).

Changelog

2024.05.15	This is the first release of QAN 003.