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Evaluating the Efficiency of Low-Cost Air Quality Sensors at a Suburban Field Site

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Abstract

Science surrounding the use of low-cost sensors (LCS) to monitor air quality is rapidly expanding to satisfy the need to fill in regional air quality data gaps. This project evaluated the suitability of two types of LCS: Modulair-PM and PurpleAir (SD and Flex models) as efficient means to measure airborne particulate matter. The study involved physical installation of nine co-located sensors at a suburban site in Denver, connectivity troubleshooting as necessary, and data analysis/modeling of data over multiple months (19 weeks). PM data was compared between individual sensors of the same type, as well as across the two different sensor models, and used to draw conclusions about air quality trends at the field site. Comparisons between sensors were generally in good agreement (R2 values of 0.98, 0.99, 1.00), but an additive bias was observed for several sensors, highlighting the importance of calibration of these types of units. The project concluded with installation of the PurpleAir units at a field site at the Kennedy Mountain Campus of the University of Denver. Results from the project create a base level of understanding of LCS functionality to be expanded upon in future project applications.

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Abstract

Science surrounding the use of low-cost sensors (LCS) to monitor air quality is rapidly expanding to satisfy the need to fill in regional air quality data gaps. This project evaluated the suitability of two types of LCS: Modulair-PM and PurpleAir (SD and Flex models) as efficient means to measure airborne particulate matter. The study involved physical installation of nine co-located sensors at a suburban site in Denver, connectivity troubleshooting as necessary, and data analysis/modeling of data over multiple months (19 weeks). PM data was compared between individual sensors of the same type, as well as across the two different sensor models, and used to draw conclusions about air quality trends at the field site. Comparisons between sensors were generally in good agreement (R^2 values of 0.98, 0.99, 1.00), but an additive bias was observed for several sensors, highlighting the importance of calibration of these types of units. The project concluded with installation of the PurpleAir units at a field site at the Kennedy Mountain Campus of the University of Denver. Results from the project create a base level of understanding of LCS functionality to be expanded upon in future project applications.

1. Introduction/Background

Air quality has large implications for human health as well as ecosystem dynamics. Air pollution is a widespread problem that can have severely negative implications on the health of plants, animals, and humans. Liquid or solid particles in the air are referred to as particulate matter (PM) and are measured according to mass concentration over a specific size range[4]. This project deals specifically with PM10, PM2.5, and PM1. The Environmental Protection Agency defines these terms as particles with diameters of 10, 2.5, or 1 µm and smaller, respectively.[5] PM10 includes, e.g. dust, pollen, and mold spores, while PM2.5 is more often dominated by combustion soot particles and organic aerosols.[5] PM comes from both natural and anthropogenic sources, such as soot from wildfires or vehicle emissions.[5] PM pollution specifically damages the cardiovascular system leading to increased morbidity and mortality among individuals exposed on both the short- and long-term[1]. Studying air quality is becoming increasingly important as climate change directly affects weather patterns and modifies the levels and types of pollutants in the atmosphere.

One scientific challenge associated with air quality is gathering enough data to visualize widespread pollutant trends across the globe, which is a first step towards finding solutions. Low-cost sensors (LCS) are a relatively recent technology that has emerged in an attempt to more easily fill gaps in air quality data. Experimenting with low-cost sensors lays the groundwork for further knowledge and progress towards cleaner air, which will save lives. Despite being produced in numerous commercial varieties, Karagulian et al. laments a “lack of exhaustive and accessible information” regarding the relative performance and advantages of each variation of LCS[2]. Specifically, the study states that “inter-comparison exercises where LCS are gathered at the same test sites and at the same time are greatly needed” in order for air quality research to expand in this direction[2]. A panel summarized by Clements et al. expresses optimism for a future of valuable scientific contributions made by LCS[3].

In this study, two Modulair™-PM low-cost air quality sensors and 7 PurpleAir sensors were purchased by the lab and used to gather and interpret air quality data from the city of Denver and the Kennedy Mountain Campus. The devices use a combination of particle-sizing technologies, an optical particle counter and a nephelometer, to estimate the mass of PM that flow through the unit and integrate this data to display PM1, PM2.5, and PM10 concentrations for every minute. All nine units were installed on September 20, 2023 in Dr. Alex Huffman's backyard, and 6 PurpleAir units were reinstalled in February 2024 at three locations at the Kennedy Mountain Campus. This paper examines the installation process and analyzes data from all sensor units over the multiple months they were situated at the suburban backyard site in Denver.

2. Methods

2.1 Instrumentation

The Modulair-PM units use a combination of size data collected by an optical particle counter (OPC) and a nephelometer. Optical particle counters detect and size particles by passing them through a beam of light and measuring the amount of light scattered by individual particles. Each pulse is assigned to a size bin based on its total light intensity, and the resulting histogram is converted to an integrated mass loading in each size range (PM1, PM2.5, PM10) once the entire distribution has been measured. Nephelometers similarly utilize scattering measurements, but unlike OPCs they take the light scattered by an ensemble of particles across a wide range of angles to avoid pure forward and backward scattering. The total scattering amplitude is correlated with a mass measurement made by a reference instrument. In the Modulair-PM units, the OPC is used to count and size particles above 350 nm in diameter, and the nephelometer is used to estimate the mass of particles that are below the detection threshold of the OPC. The nephelometer is unable to detect particles larger than 1 µm in diameter.

Air sampled by the Modulair-PM units is split into channels for the OPC and nephelometer. After the sample period of 1.5 s, the spectra from both instruments are combined and the total mass loading is calculated. Several internal corrections are made during the calculations before PM data is released, such as correcting for aerosol density, aspiration efficiency, and environmental factors such as high humidity.

The PurpleAir sensors function with a similar process, using Plantower PMS*003 and series laser counters to size particles from 0.3 to 10 µm in diameter.[6] Each sensor contains two laser counters that alternate and average five-second readings over two minutes.[6] They function by recording the laser reflections caused by particles as pulses on a detection plate, and inferring mass concentration values based on the number and length of resultant pulses.[6] Real time values for PM10, PM2.5, and PM1 are reported to the cloud and can be accessed on PurpleAir's public access community map.[6] The sensors are also equipped to gather pressure, temperature, and humidity data.[9] Two models of PurpleAir sensors were employed in this study: the PurpleAir Flex and the PurpleAir SD-II. Both models are advertised to function identically, however, the Flex sensor is the more updated model which uses a Plantower PMS6003 sensor compared to the SD-II which uses a Plantower PMS5003.[9] Additionally, the Flex model does not have an SD card, and only stores data to the cloud for up to two years.[9] The SD model has local storage capacity on the SD card as well as the same cloud storage capacity as the Flex model.[9]

The most notable difference between the Modulair-PM units and the PurpleAir sensors is that the Modulairs rely on cellular data to report data while the PurpleAirs connect to local Wi-Fi networks. Both types of units retain the option of locally storing data via microSD cards. Another stark difference between the two brands is the price per unit, with PurpleAir Flex and SD costing in the range of $250-$300 with free access to data downloads,[7] and Modulair-PMs costing $1995/unit plus $500/unit/year of data access.[8] Finally, the raw size data was downloaded in 1 minute averages from the Modulairs, and in 10 minute averages from the PurpleAirs.

2.2 Deployment on-site

Planning in-lab before on-site deployment consisted of measuring sensor dimensions, sawing wood, and affixing sensors. The two Modulair sensors were screwed into a small panel of wood alongside each other, 3 inches apart. The seven PurpleAir sensors were screwed 1.5 inches apart and alternating on each side of a long 2" x 4" boards. The sensors were clustered on either ends of the 2x4 with the intention of leaving space in the center for the Modulair units. A diagram of the imagined setup is pictured in Figure 1.

On-site deployment occurred on 9/20/24 at Dr. Huffman's house in Centennial, Colorado. A platform was leveled and a base pole was secured against the ground and a wooden fence. The 2x4 with PurpleAir units on each side was screwed into the base near the top, and the panel containing the Modulairs was screwed in the center of the structure directly below the 2x4. Cords plugged into each sensor were untangled and secured using zip ties. These cords were run along the fence and plugged into a nearby power strip located under an overhang. Figures 2 and 3 show pictures of the site setup. The final step for setup was connecting the PurpleAirs to the local Wi-Fi network.

The site setup was intended to maximize airflow to all 9 sensors, without being so close as to have interference between sensor fans. As a result, all sensors were at least 1.5 inches away from each other, and the entire structure was not placed against a solid building but rather extends upright from the fence into open air. Sensors were close enough to read similar air quality data for the intended intercomparison.

2.3 Igor Graphing

Once the instruments were deployed, preparations were made for data acquisition and analysis. Test data from Modulair and PurpleAir units was downloaded from their respective data access websites into excel sheets, and then imported into IgorPro. Date and time data from Modulairs had to be modified in format to align with IgorPro coding software. Once the data-uploading procedure was refined and mastered, a “smoke test” was conducted by lighting a match at a specific local time and letting it smoke near the sensors. The smoke test ensured that the sensors were sufficiently calibrated to read a data spike in PM pollution from an intensely localized source (Figure 4). The smoke test also revealed the time zones in which data was being reported for each sensor, which were subsequently adjusted to match local Colorado time (MT).

3. Results

3.1 Time Series

Data was regridded such that points from all sensors could be plotted along the same axes. A time series of PM10, PM2.5 and PM1 for all sensors across the entire intercomparison period is shown in Figure 5. Inspecting this graph reveals general agreement among sensors in terms of reading spikes and a general range of PM values. Sensor agreement is further evident in a scaled up cross section of PM10 values in Figure 6.

3.2 Instrument Intercomparison

PM10, PM2.5, and PM1 values for each sensor were plotted against other sensors, and the resulting scatter plots were used to draw conclusions about how well each sensor correlated with other sensors. If two sensors reported exactly equal values across the entire intercomparison period, the slope of the scatter plot would theoretically be a 1:1 correlation with a slope and R^2 value of 1. Experimental data showed that some sensors were closer to those theoretical values than others. Figure 7, for example, shows a sample poor PM10 correlation between Modulair unit 21 and PurpleAir sensor S6. The slope of 0.52 and R^2 value of 0.47 indicate stark differences between PM10 values reported by each sensor. Figure 8, for a contrasting example, shows a sample good correlation between PM10 values of S4 versus S6 (both PurpleAir sensors). This scatter plot is nearly a 1:1 correlation, with a slope of 1.01 and an R^2 value of 1.00.

Figure 11 shows a matrix of R^2 values for PM10 scatter plots. As per the color scale, the lighter colored squares indicate higher R^2 values that were closer to 1, indicating strong correlation, while the darker colored squares indicate lower R^2 values, indicating poor correlation. Generally, the most well correlated sensors were between two PurpleAir units, specifically when two Flex units were compared. The least well correlated comparisons resulted when Modulair were compared to either style of PurpleAir sensor. These results may be due to instrumental differences or have been impacted by the loss of data points due to cellular connectivity issues among the Modulairs.

3.3 Intercomparison by PM

PM10 vs PM2.5 for individual sensors were also plotted as scatter plots for analysis. Figure 9 shows PM10 vs PM2.5 for Mod 22, a Modulair unit. Figure 10 shows PM10 vs PM2.5 for S4, a PurpleAir unit. Both scatter plots show data close to a 1 to 1 correlation, indicating that the majority of PM10 values being reported are dominated by the PM2.5 signal.

4. Summary/Conclusions

The project established foundational understandings of instrument installation and function, contributing to the larger need to fill particulate matter research gaps in the United States. It revealed the respective advantages and disadvantages of two types of LCS, Modulair and PurpleAir. The project also established a procedure for graphing and manipulating PM data in Igor Pro.

The largest limitation of the project was the cellular connectivity issues with both Modulair units. Figure 12 shows an example of a time series of both Modulair units showing large gaps in PM10 data points when one sensor (blue) goes offline. The PurpleAir sensors faced their own difficulties as well. First, Figure 13 indicates a problem in calibration of the S0 PurpleAir sensor (red) when compared with the rest of the PurpleAir sensors. There is a significant difference in values, however, the peaks and troughs are replicated by the S0 line, pointing towards calibration error. Finally, Figure 14 shows a period of incredibly large PM10 values for the S1 PurpleAir sensor. We conclude this to be a result of debris interfering with the instrument’s fan.

Observations from this project will be used for further experimentation with air quality sensors and the acquisition of quantitative data. Six PurpleAir sensors were installed at 3 sites at the Kennedy Mountain Campus in January 2024 and are currently logging PM data. Each site consists of one SD and one Flex model situated as in the intercomparison period to maximize airflow for best results. One of the sites is pictured in Figure 15. This is the first research effort deployed at the campus. The University of Denver plans to increase data collection and scientific exploration in future years using LCS and eventually installing a meteorological station. Observations from the intercomparison period will be imperative when considering data from the higher-altitude site.

Other future work could include a reinstallation of the Modulair units in an area with better cell coverage, or alongside a cell signal booster, as they were not installed at the KMC due to a total lack of cell coverage in the area. It would be beneficial to cross-reference data from the LCS with a more established and expensive instrument to verify the accuracy and not just the precision of the small sensors.

5. Tables and Figures

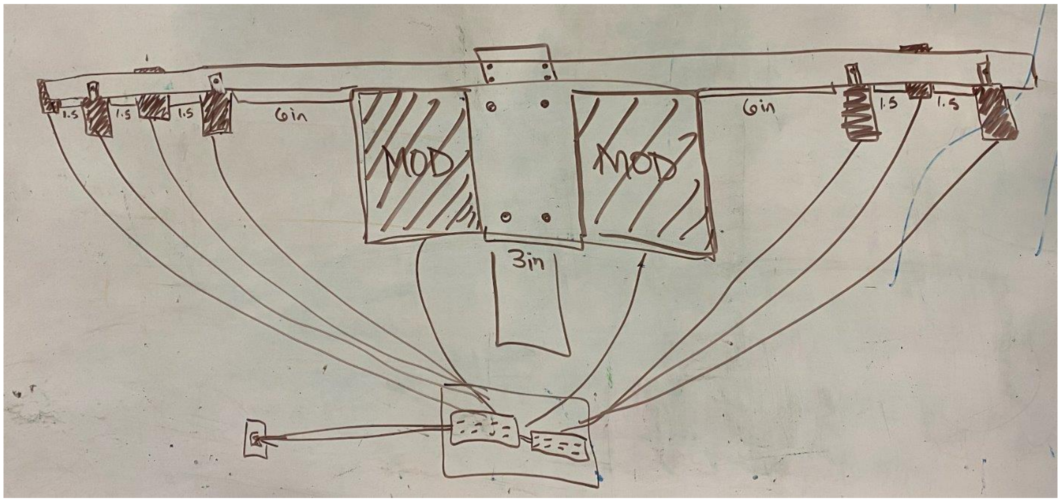

Figure 1: Diagram of imagined on-site deployment setup of 6 PurpleAir and 2 Modulair sensors

Figure 2: Suburban site setup (Angle 1)

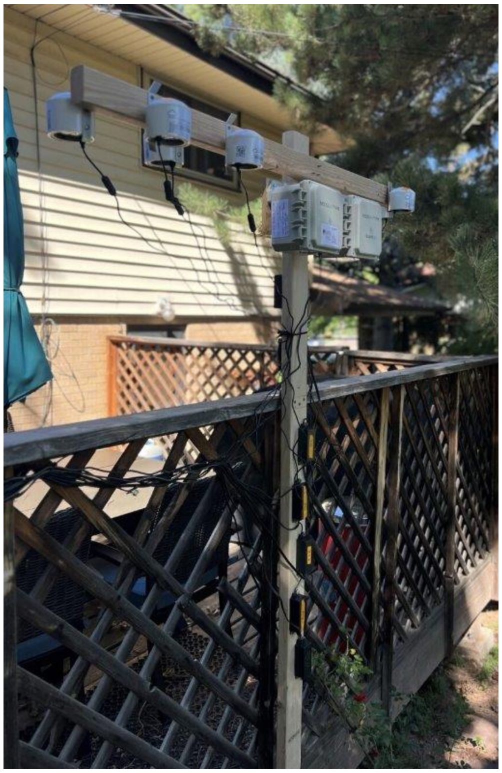

Figure 3: Suburban site setup (Angle 2)

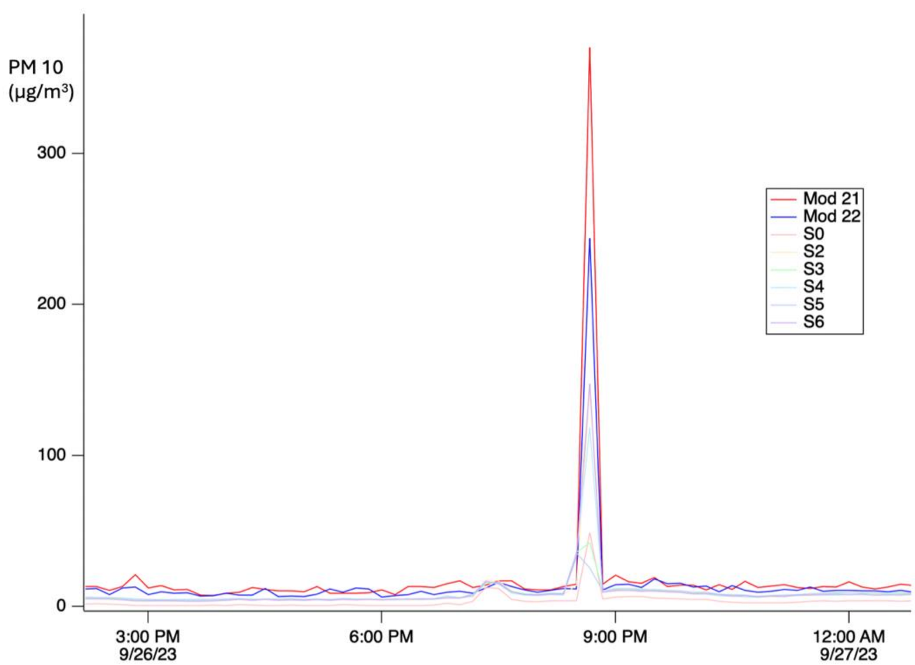

Figure 4: PM10 time series with “smoke test” peak

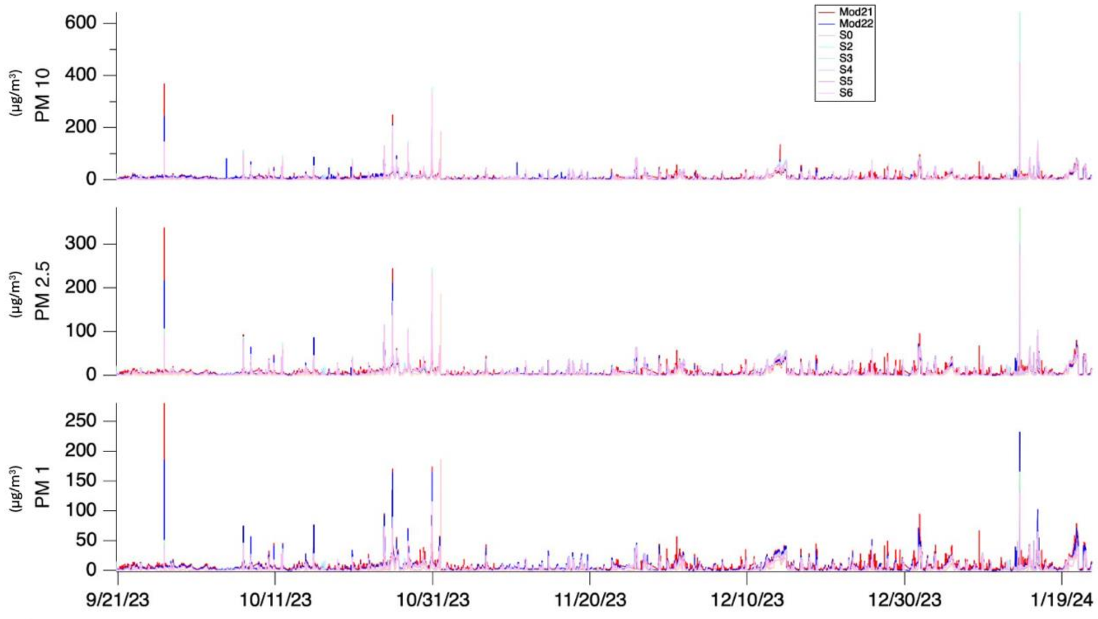

Figure 5: Time series of PM1, PM2.5, and PM10 over the intercomparison period

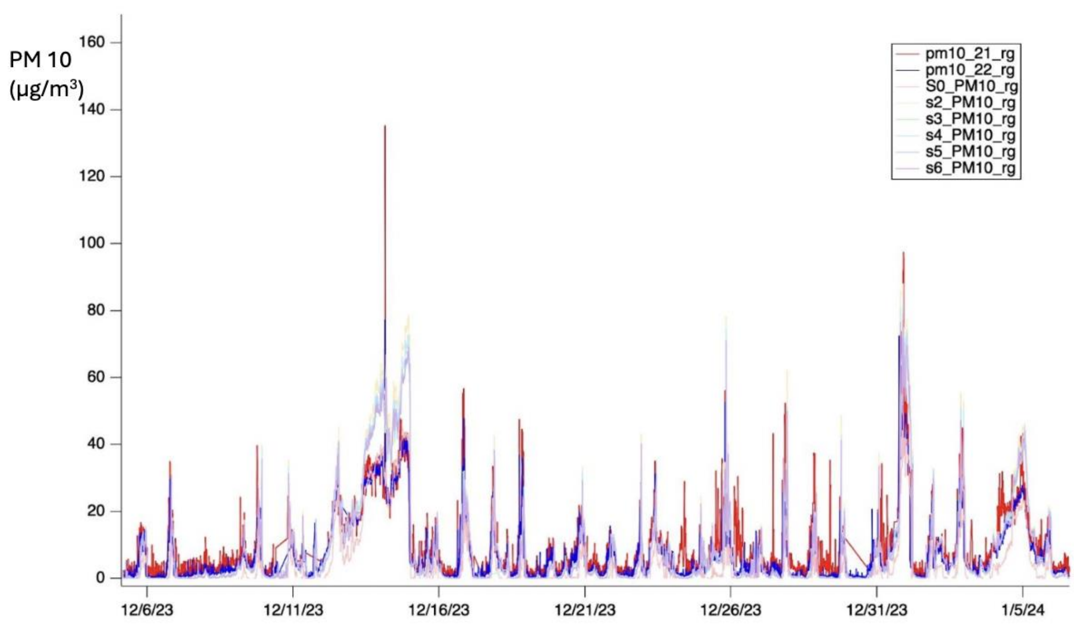

Figure 6: PM10 time series, magnified on time axis to show more detail

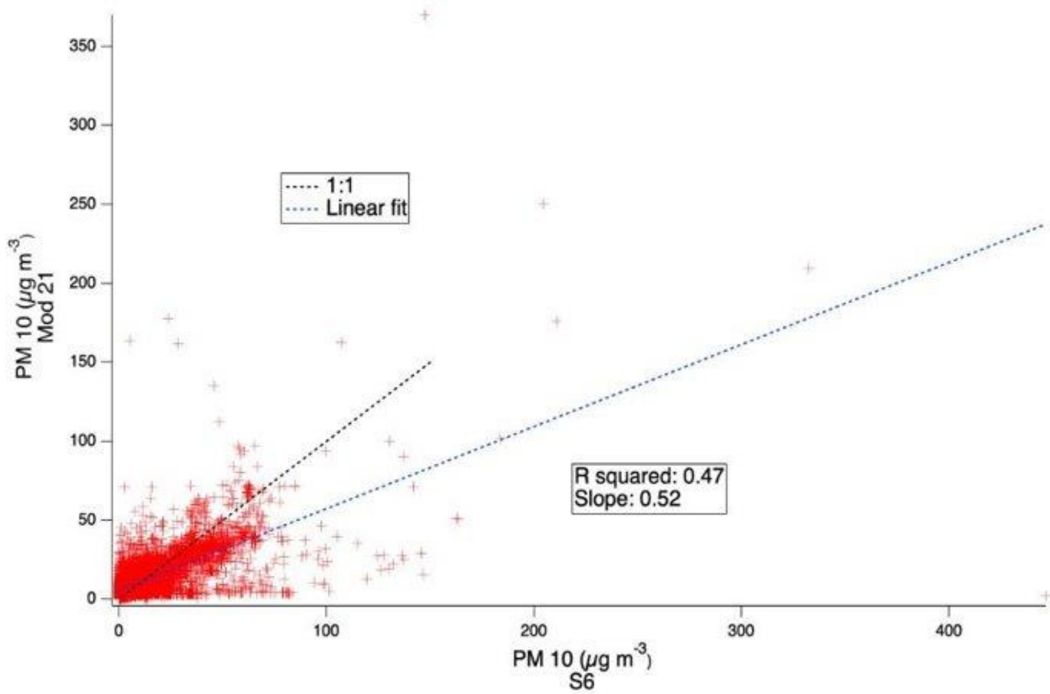

Figure 7: PM10 values, Mod 21 (Modulair) vs S6 (PurpleAir Flex)

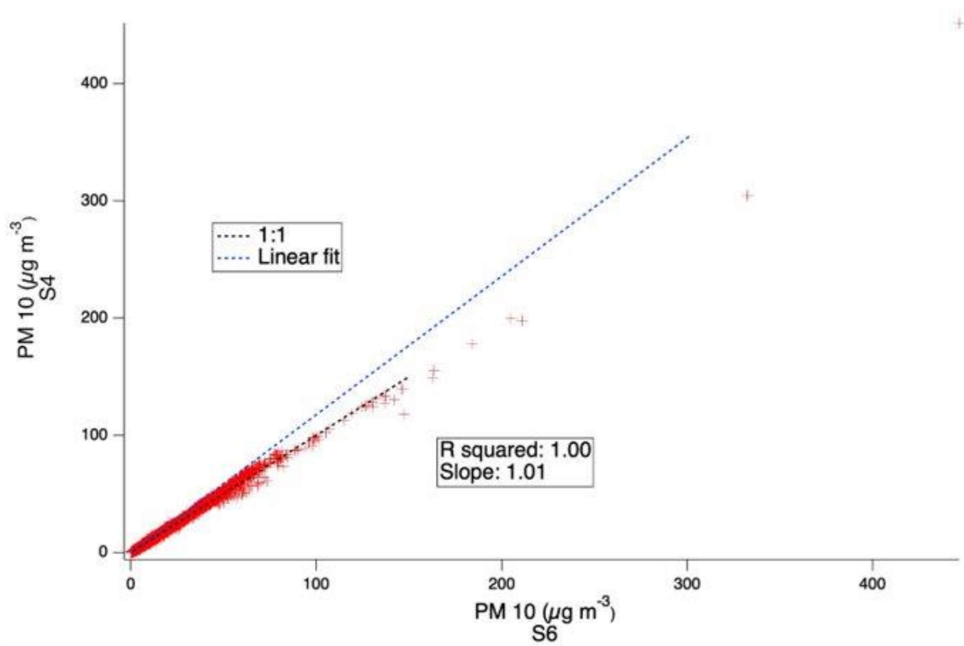

Figure 8: PM10 values, S4 (PurpleAir Flex) vs S6 (PurpleAir Flex)

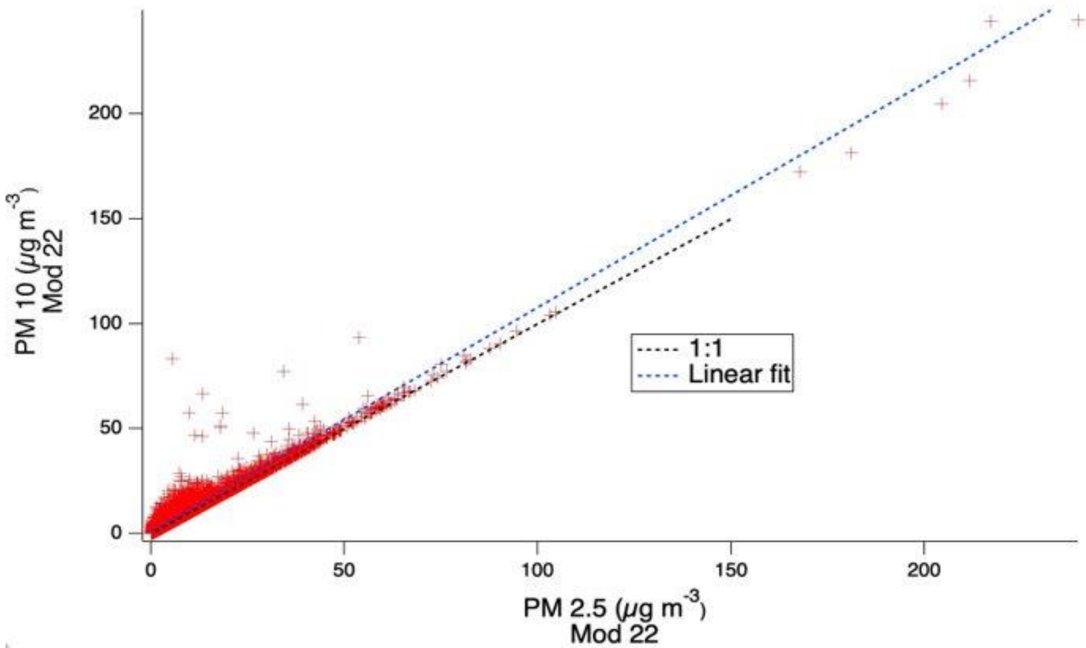

Figure 9: Mod 22 (Modulair), PM10 vs PM2.5

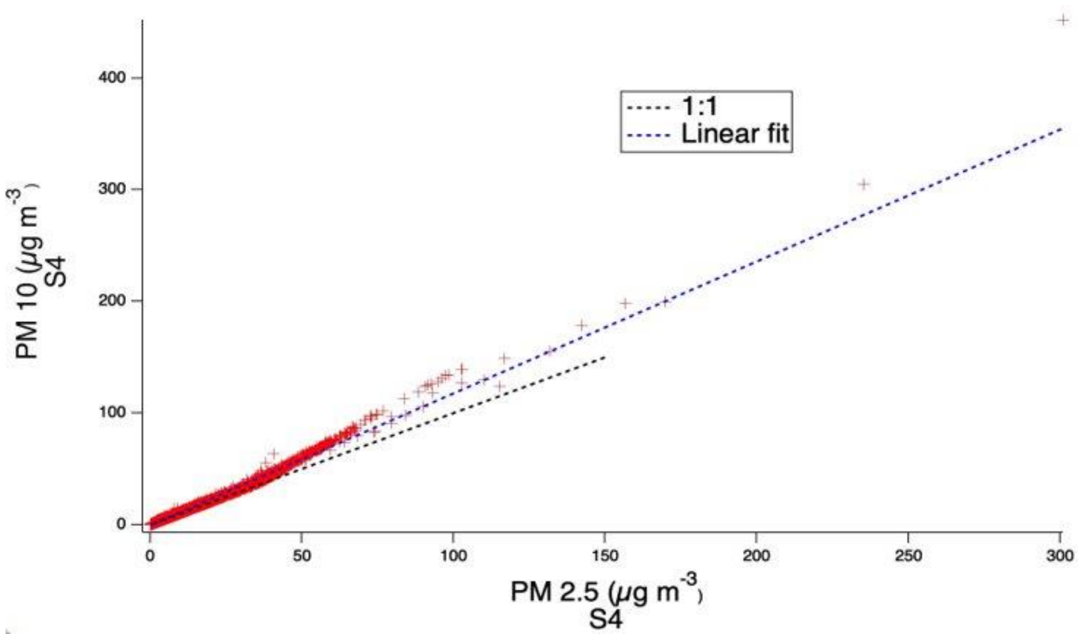

Figure 10: S4 (PurpleAir Flex), PM10 vs PM2.5

	UNIT	Mod21	Mod22	S0	S1	S2	S3	S4	S5	S6
UNIT	Sensor type	Modulair-PM		SD	SD	Flex	SD	Flex	SD	Flex
Mod21	Modulair-PM		0.74	0.49	0.56	0.45	0.56	0.48	0.55	0.47
Mod22				0.62	0.69	0.60	0.69	0.64	0.69	0.64
S0	SD				0.83	0.75	0.91	0.79	0.90	0.78
S1	SD					0.78	0.91	0.83	0.90	0.81
S2	Flex						0.85	0.99	0.86	0.99
S3	SD							0.89	0.98	0.87
S4	Flex								0.91	1.00
S5	SD									0.90
S6	Flex									

	0.95 – 1.0
	0.90-0.95
	0.80 – 0.90
	0.70 – 0.80
	0.60 – 0.70
	< 0.60

Sensor Type Key	
Mod21, Mod22	Modulair^{TM}-PM
S0-S6	PurpleAir (Flex or SD)

Figure 11: Matrix of R^2 values for PM10 values of all sensors

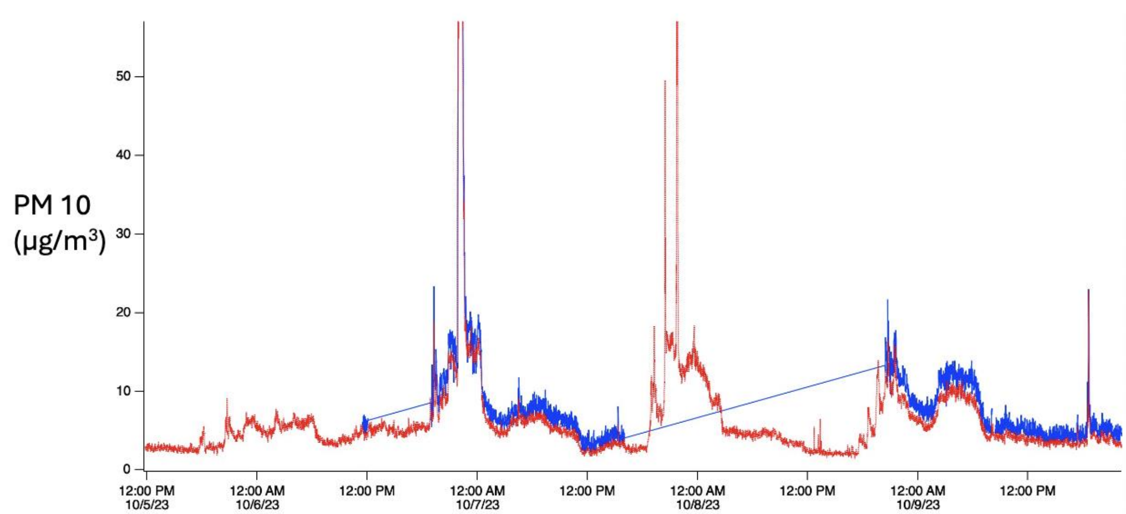

Figure 12: Scaled up cross section of PM10 values for Mod 21 (blue) and Mod 22 (red)

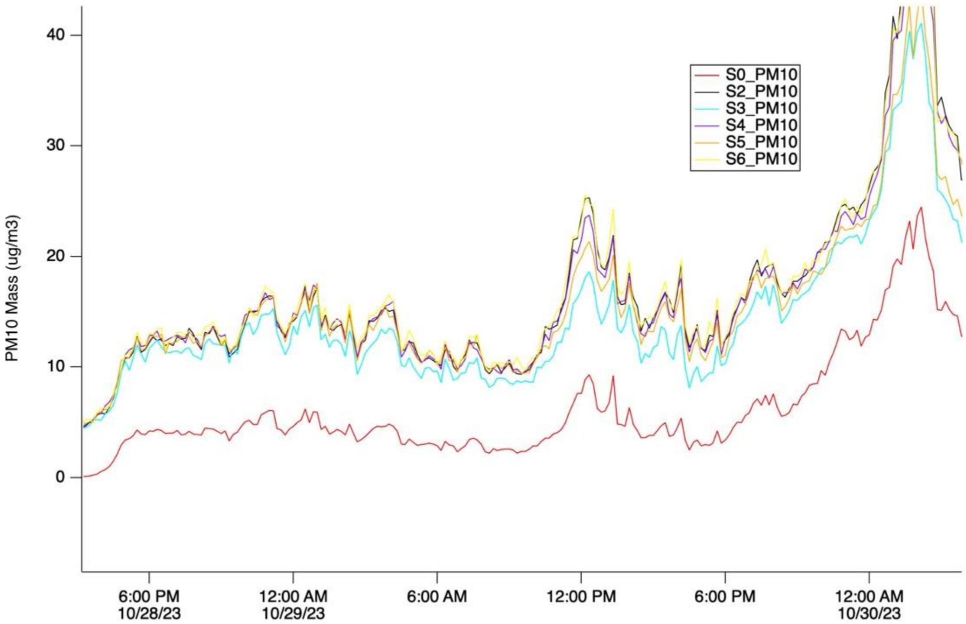

Figure 13: Calibration difficulties of S0 (PurpleAir SD) (red) compared with other PurpleAirs

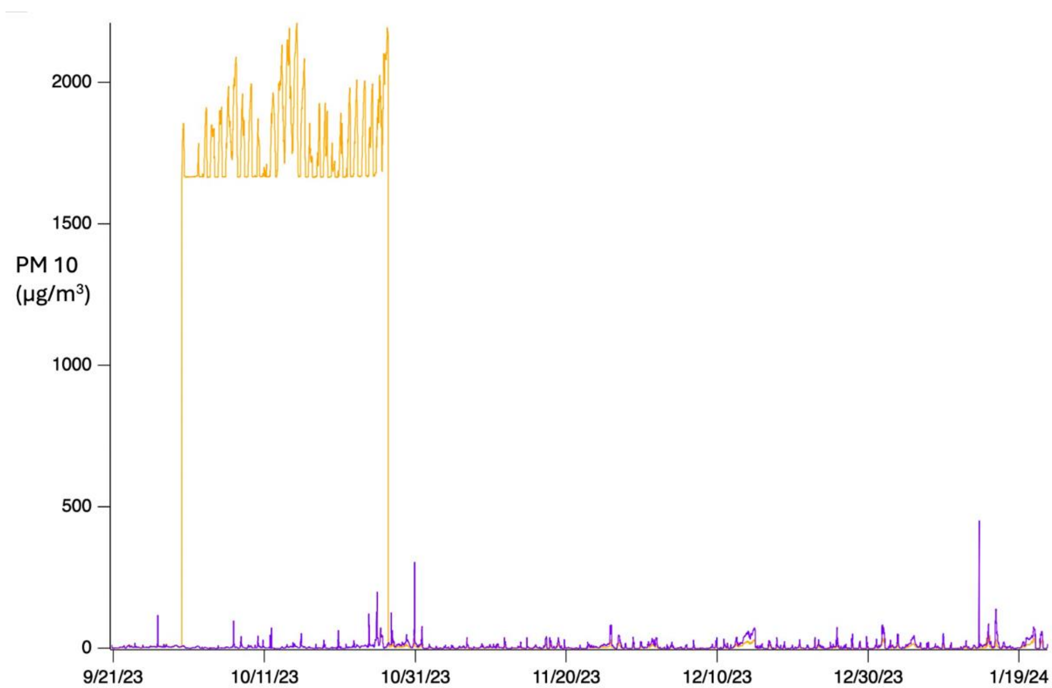

Figure 14: Fan interference in S1 (PurpleAir SD) (orange) compared with other PurpleAirs

Figure 15: PurpleAir site at KMC

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