UNDERSTANDING AND EVALUATING LIMITATIONS OF LOW-COST AIR SENSORS

Prepared for

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Introduction

The U.S. Environmental Protection Agency (EPA) is reconsidering the primary and secondary standards for particulate matter (PM) $_{2.5}$. While EPA recently proposed to maintain the current secondary standards for PM 2.5, the Agency proposed to lower the annual primary standard for PM2.5 to a range of 9 to 10 µg/m3.[1] RLR Consulting is aware of the recent increase in use of what are commonly referred to as "low-cost sensors" to measure ambient air quality. The Institute for Energy Research commissioned this paper because low-cost sensors are being used to drive public policy objectives and having a better understanding of their capabilities is key when using their data to make policy changes. While these devices have been used in many states throughout the country, this paper focuses on their use in Florida given the state's unique climate and the very public use of these low-cost devices.

Among the more prominent makers of low-cost sensors being deployed in Florida are those supplied by PurpleAir. PurpleAir sensors are used to monitor PM concentrations in the air ambient air. The purpose of this paper is to present the results of a literature review that focused on potential data quality issues that could arise from the use of PurpleAir monitors.

Key Findings:

- EPA scientists have found that PurpleAir monitors are biased and consistently overstate fine particle concentrations.
- EPA scientists have identified numerous data quality issues with PurpleAir monitors.
- The founder and creator of PurpleAir monitors has acknowledged inaccuracies when dealing with humidity, especially greater than 60 percent.[2]

Reference Methods and Equivalent Methods

Monitoring of atmospheric air quality for purposes of determining compliance with EPA's National Ambient Air Quality Standards (NAAQS) requires the use of either federal reference methods (FRMs) or federal equivalent methods (FEMs). Such "compliance" monitoring is primarily carried out by State and local governmental air pollution control agencies. Requirements and procedures by which ambient air monitoring methods for NAAQS pollutants may be designated by EPA as FRMs and FEMs are codified in 40 CFR Part 53. This regulation provides detailed procedures for testing candidate methods as well as the formal technical and non-technical requirements for submitting applications to EPA for reference or equivalent method determinations. EPA has recognized that low-cost air sensors will not meet the stringent requirements for air quality instruments used for regulatory purposes.[3] To date, RLR Consulting has found no evidence of a single supplier of low-cost sensors, including PurpleAir monitors, even applying for FEM status much less achieving FEM status.

[1] 88 Fed. Reg., 5558 (January 27, 2023)

[2] https://www.youtube.com/watch?v=LturaCFNz0k

[3] https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols#:~:text=EPA%20has%20recognized%20that%20air,to%20identify%20sites%20for%20regulatory

Network Design

EPA has published detailed procedures for designing an ambient air monitoring network. One of primary considerations is to determine the purpose of the monitoring network. Rather obvious purposes include (1) determining if an area is attaining the NAAQS; (2) determining the impact of significant sources or source categories on air quality; and (3) determining background concentrations. EPA provides some of the following specific guidance for monitoring placement. Because obstructions such as trees and fences can significantly alter the air flow, monitors should be placed away from obstructions. It is important for air flow around the monitor to be representative of the general air flow in the area to prevent sampling bias. The siting of the individual sensors is critical if representative ambient air PM concentrations are to be determined. Poorly sited sensors can be influenced by local sources (e.g., backyard barbeque grill, vehicle exhaust, etc.), which can influence readings that are not truly representative of ambient air.

Low-Cost Sensors - General

Over the last few years low-cost sensors that are purported to monitor particulate matter (PM) concentrations as well as gaseous pollutants in the ambient air have become ubiquitous. In general, low-cost sensors are lower in cost, portable and easier to operate than regulatory-grade monitors (i.e., FRMs or FEMs). Analysis of the data from low-cost monitors show there is a price to be paid with respect to data quality in exchange for simplicity and ease of operation.

EPA's Office of Research and Development (ORD) has prepared the following table to compare and contrast low-cost sensors with EPA-approved methods.

Reference Monitors Versus Low-Cost Sensors

	Reference Monitors	Low-Cost Sensors
Price Range	\$15,000 to \$50,000	\$100 to \$2,500
Operating Expense	Expensive	Inexpensive
Siting Location	Fixed Location (building/trailer required)	Portable (basic weather shielding)
Staff Training	Highly trained technical staff	Little or No Training
Data Quality	Known and consistent quality in a variety of conditions	Unknown and may vary from sensor to sensor and in different weather conditions
Operating Lifetime	10^{+} years (calibrated and operated to maintain accuracy)	Short (1 year) or unknown (may become less sensitive over time)
Used for Regulatory Monitoring	Yes	No

Low-Cost Sensors – PurpleAir

Perhaps none of the low-cost sensors are more prevalent than those furnished by PurpleAir. While a number of PurpleAir sensors have been deployed, it is important to remember that PurpleAir sensors are neither FRMs nor have they achieved FEM status.

PurpleAir sensors use a fan to draw air past a laser, causing reflections from particles in the air. According to the literature, the PurpleAir sensor contains two Plantower PMS5003 sensors, labeled as channel A and B, which operate for alternating 10 second intervals and provide 2-minute averaged data. Plantower sensors measure 90° light scattering with a laser using 680 ± 10 nanometers (nm) wavelength light and are factory calibrated using ambient aerosols. The Plantower sensor records particle counts of particles with aerodynamic diameters < 1 micrometer (µm) ($PM_{1.0}$), < 2.5 µm $PM_{2.5}$, and < 10 µm (PM_{10}). These particle counts are then processed by the sensor using a built-in algorithm to estimate $PM_{1.0}$, $PM_{2.5}$ and PM_{10} mass concentrations in the units of µg per cubic meter (µg/m^3).

EPA scientists have found that PurpleAir sensors are biased -- they consistently overpredict fine particle concentrations in most locations and under higher humidity compared to the regulatory-grade monitors that are operated in the same location. EPA's research examined the effect of relative humidity, ambient temperature, and dew point upon the responses of PurpleAir sensors to ambient PM2.5 concentrations. Of these three independent variables, EPA determined that relative humidity had the most explanatory power in terms of relating responses from PurpleAir sensors to EPA reference method data. EPA published the following PurpleAir correction equation with the title, "2019 US-wide correction built."[4]

$$PM_{2.5} = 0.52 \times PA_{cf\_1} - 0.86 \times RH + 5.75$$

Where:

$PM_{2.5}$ = PurpleAir corrected $PM_{2.5}$ concentration, µg/m^3

PA_{cf_1} = response from PurpleAir sensor[5]

RH = relative humidity, %

It may be helpful to present some numerical examples utilizing the above-cited EPA correction equation. Let's assume two PurpleAir sensor readings of 10 and 30. Next, correct the PurpleAir readings for three distinct relative humidity values equal to 20, 60 and 90 percent. The results are shown in the table below.

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[4] Barkjohn, Karoline K., et al., "Development and Application of a United States-wide Correction for $PM_{2.5}$ Data Collected with the PurpleAir Sensor," *Atmospheric Measurement Techniques*, 14: 4617 – 4637.
[5] Ibid, PurpleAir values are recorded and reported in two ways and are labeled as cf_1 and cf_atm, respectively. The two data columns have a [cf_atm] / [cf_1] = 1 relationship below approximately 25 µg/ m^3 but transitions to a 2/3 ratio at higher concentrations with the cf_1 values being higher of the two.

Purple Air	Corrected $PM_{2.5}$ Concentration (μg/m^3)		
Result (μg/m^3)	RH = 20 %	RH = 60 %	RH = 90 %
10	9.2	5.8	3.2
30	19.6	16.2	13.6

Thus, if the relative humidity were 60 percent (which is near the lowest humidity found in South Florida during the year) and the PurpleAir monitor were to read 10 μg/m^3, then the corrected value would be 5.8 μg/m^3. More recent EPA research has shown that the relationship between the responses from PurpleAir sensors and EPA reference monitors not only vary based on relative humidity but also on the true ambient $PM_{2.5}$ concentrations. In other words, EPA determined that different equations are needed to adjust the PurpleAir data depending upon the actual ambient $PM_{2.5}$ concentration as determined by reference method monitors. EPA's latest work indicates that the above-cited correction equation should be used for low ambient concentrations (i.e., $PA_{cf\_atm} < 50$ μg/m^3. EPA has developed additional correction equations for higher ambient concentrations.

PurpleAir Data Quality Issues

One of major deficiencies with most low-cost sensors, including PurpleAir monitors, is the failure to include any onboard diagnostic outputs. Onboard diagnostic outputs can alert the operator to various sensor problems such as excessive drift and outright sensor failure. Without any diagnostic signals, a data analyst may resort to developing various subjective criteria for evaluating sensor data quality. For example, a data analyst might specify a given difference (delta) between the PurpleAir A and B channels within which both readings must fall in order to be considered valid. Likewise, a data analyst might decide if PurpleAir Sensor Y reads twice as high as surrounding sensors, then Sensor Y has suffered a failure. RLR Consulting is not necessarily criticizing the above-discussed data quality examples. Rather, RLR Consulting is pointing out that such criteria are subjective and not likely to be applied uniformly across many potential data analysts.

EPA's Office of Air Quality Planning and Standards (OAQPS) has examined data quality associated with low-cost sensors and has identified the following concerns:[6]

- Lack of systematic data quality characterization
- Disparity in how well technologies perform under various meteorological conditions
- Variations in meeting basic data quality indicators of performance (e.g. accuracy and precision)
- Uncertainty in how long the devices perform over time
- Questions in accuracy of measurements near sources.

[6] "Air Sensors – An EPA Perspective," presentation to EPA's Clean Air Act Advisory Committee (CAAAC), by EPA's OAQPS, September 2018.

Conclusions

Currently, there are numerous PurpleAir sensors in operation across the United States. While PurpleAir sensors can be relatively simple to deploy, as discussed above, the location and placement of the individual sensors are critical to collecting representative ambient air quality data. Moreover, relative humidity has a significant impact on the relationship between PurpleAir sensor readings and "true" ambient air PM concentrations.

Because the relative humidity in south Florida is very high relative to much of the rest of the country, the use of PurpleAir sensors in the state should raise concern. As other researchers have shown, the raw responses from PurpleAir sensors must be "corrected" if they are to approach the readings that would be obtained from either FRMs or FEMs. However, substantive questions remain as to whether a correction equation based on nationwide data is appropriate for use in Florida, which is characterized by both elevated temperatures and relative humidity.