Particulate Matter Sensor Operating Procedure

By

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For the

Air Quality Program

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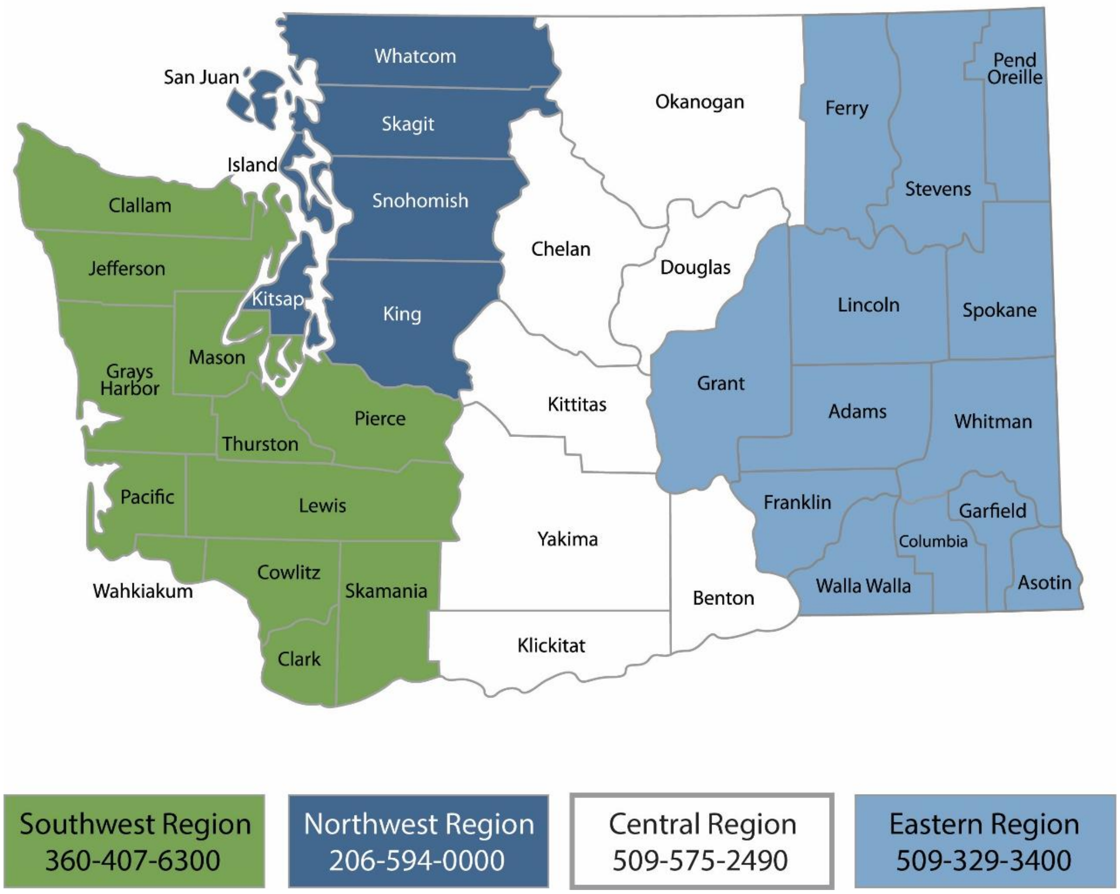
Department of Ecology's Regional Offices

Map of Counties Served



Region	Counties served	Mailing Address	Phone
Southwest	Clallam, Clark, Cowlitz, Grays Harbor, Jefferson, Mason, Lewis, Pacific, Pierce, Skamania, Thurston, Wahkiakum	PO Box 47775 Olympia, WA 98504	360-407-6300
Northwest	Island, King, Kitsap, San Juan, Skagit, Snohomish, Whatcom	PO Box 330316 Shoreline, WA 98133	206-594-0000
Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 W Alder St Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
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DEPARTMENT OF ECOLOGY
State of Washington

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Revision History

Revision Date	Revision Number	Summary of changes	Revised sections	Revised by
06/11/2024	1.0	Initial Publication		Christopher Atherly

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Acronyms and Abbreviations

AAMG	Ambient Air Monitoring Group
AMTIC	Ambient Monitoring Technology Information Center
APTI	Air Pollution Training Institute
AQI	Air Quality Index
AQP	Air Quality Program
AQPLT	Air Quality Program Leadership Team
AQS	Air Quality System
BAM	Beta Attenuation Monitor
CRO	Central Region Office
DQO	Data quality objective
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
ERO	Eastern Region Office
FEM	Federal Equivalent Method
FRM	Federal Reference Method
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MQO	Measurement Quality Objectives
NAAQS	National Ambient Air Quality Standards
NRMSE	Normalized Root Mean Squared Error
NWRO	Northwest Region Office
PM	Particulate Matter
$PM_{2.5}$	PM less than or equal to 2.5 micrometers in diameter
PM_{10}	PM less than or equal to 10 micrometers in diameter
OLS	Ordinary Least Squares
OPC	Optical Particle Counter
PQAO	Principal Quality Assurance Organization
QA	Quality assurance
QAP	Quality Assurance Plan
QAPP	Quality Assurance Project Plan

QC	Quality control
RH	Relative Humidity
RHTP	Relative Humidity, Temperature, and Pressure
RMSE	Root Mean Squared Error
SCAQMD	South Coast Air Quality Management District
SOP	Standard Operating Procedure
SWRO	Southwest Region Office
T	Temperature

1. Introduction

1.1. Purpose and scope

This document describes the standard operating procedures for PM sensor monitoring within the Washington State Ambient Air Monitoring Network (Washington Network) managed by Ecology. It covers PM sensor measurement principles, the collocation-correction process used in place of calibration, as well as installation, QC, and maintenance.

PM sensor applications include temporary monitoring of smoke from wildland fires, response to isolated or emergent events, monitoring to aid in smoke management decisions, surveys or saturation studies of unmonitored areas, and high-density monitoring of overburdened communities.

Ecology's Air Sensor Policy approved by the Monitoring Advisory Committee defines three tiers of PM sensors based on model and level of QC. PM sensors in Ecology's Tier 1 (PurpleAir) are for informational purposes and are not covered here. This document only applies to the Ecology SensWA (Section 5) and QuantAQ MODULAIR-PM (Section 6) that Ecology uses under the more rigorous PM sensor monitoring standards of Tiers 2 and 3.

Ecology's choice of PM sensors relies on work from outside agencies such as the EPA and the SCAQMD. These agencies are funded and equipped to conduct extensive sensor evaluations, and Ecology uses their results to select the highest-performing sensors. Ecology also evaluates selected PM sensors at monitoring sites in across Washington to understand their suitability for the state's diverse environmental conditions.

1.2. PM sensor background

PM sensors offer a valuable complement to traditional air quality monitoring methods. While they are non-regulatory, they do have several advantages, including their lower cost, smaller size, and lesser maintenance demands. Sensors have advanced to the point that they compare favorably to FEMs, and offer minimal data loss, low inter-sensor variability, reasonable correlation with regulatory measurements, and reasonable life span.

PM sensors do have limitations, including less diagnostic information, sensitivity to humidity, non-linearity at high concentrations, sensitivity to PM optical properties, and their inability to adjust settings.

PM sensors can provide accurate estimation of PM concentrations, but only with proper data correction and QC.

1.3. PM sensor measurement principles

PM sensors combine hardware, software, and one or more sensing elements to measure PM concentrations. The PM sensing elements (sometimes called PM sensors themselves) are often referred to as particle counters and use a light source (typically a laser) to illuminate particles in sampled air. The light scattered by these particles is then focused onto a detector to count individual particles.

Examples of PM sensing elements are the Sensirion SPS30, used in Ecology's SensWA, and the Plantower PMS500, used in PurpleAir and QuantAQ MODULAIR-PM.

The measurement method of PM sensing elements is not well defined by their manufacturers and is an active topic of research. Current understanding suggests their behavior aligns more closely with imperfect optical particle counters than nephelometers (Kuula et al., 2020; J. Ouimette et al., 2022, 2023; Molina Rueda et al., 2023). This imperfection arises because most particles don't perfectly align with the laser beam, leading to potential undercounting or under-sizing. Ecology continuously monitors research advancements in this field and will update its guidance accordingly.

PM sensing elements measure PM_1 (PM < 1 µm diameter) most accurately. $PM_{2.5}$ (PM < 2.5 µm diameter) is estimated with reasonable accuracy, but PM_{10} (PM < 10 µm diameter) signals of PM sensing elements do not correlate with regulatory monitors. The inability of PM sensing elements to sense coarse PM (particles 2.5–10 µm) could be because:

- The truncated measured scattering angle, the wavelength of light, and other optical characteristics of PM sensing elements limits detection of light scattering from coarse PM.
- The inlet orientation of PM sensing elements can result in significant aspiration losses of coarse PM, with further loss of particles due to inertial impaction on internal walls.

Because of these limitations, Ecology does not use SensWA to monitor PM_{10}.

In contrast, true laser particle counters (such as the Alphasene model the QuantAQ MODULAIR-PM uses to measure PM_{10}) accurately size and count individual particles, particularly coarse PM. PM_{10} measurements from these particle counters correlate well with regulatory monitors (Crilley et al., 2018; Kaur & Kelly, 2023; Sousan et al., 2016). Currently, Ecology only uses sensor PM_{10} measurements from QuantAQ MODULAIR-PM.

1.4. Factors affecting PM sensors

PM sensor data quality can be influenced by various factors affecting light-particle interactions. These include the difference in light scattering properties of different-sized particles and the influence of environmental factors like humidity.

Fortunately, prior research (Alfano et al., 2020; Barkjohn et al., 2021; deSouza et al., 2022; Ghamari et al., 2022; Giordano et al., 2021; Hong et al., 2021; Raysoni et al., 2023; Roberts et al., 2022) and Ecology's evaluations have shown these factors are correctable, enabling high-quality data from PM sensors.

1.4.1. Meteorology

Meteorological conditions such as ambient temperature and relative humidity can affect PM sensor performance (Barkjohn et al., 2021; Tagle et al., 2020; Wang et al., 2021). Meteorological factors include:

- **Water absorption:** Unlike other PM monitors in the Washington Network, PM sensors used by Ecology do not include inlet heaters or dryers. As a result, water vapor can be absorbed by PM. This alters the light scattering properties of PM and can lead to inaccurate sensor readings.

- **Fog**: Consisting of water droplets or ice crystals, fog can interfere with the scattering signal and lead to erroneous readings.
- **RH**: Sensor data is typically affected when RH exceeds 75%.
- **Temperature**: While extreme high or low temperatures alone have minimal effects, some regions have reported false high PM concentrations during periods of both high temperature and humidity. Nationwide studies typically focus on correcting for the combined effects of temperature and RH (Barkjohn et al., 2021).

Ecology has found that SensWA $PM_{2.5}$ sensors can meet or exceed data quality targets with straightforward correlation methods that do not include humidity or temperature interference corrections. However, Ecology has found that QuantAQ MODULAIR-PM PM_{10} sensors deployed in the Washington Network report false high concentrations when low temperatures and high humidity co-occur.

1.4.2. PM physiochemical properties

PM size, shape, and chemical composition play a significant role in PM sensor performance by changing how light scatters off particles. Further complicating issues, sensors measure a particle's size. Therefore, changes in particle density will affect mass calculations. These effects significantly affect light-scattering responses and sensor accuracy during real-word uses (Hagan & Kroll, 2020).

However, these effects can be mitigated by developing correction factors specific to PM composition. Ecology defines one set of correction factors for use during wildfire events, and another to be used all other times.

1.4.3. Ambient deployment

Ambient deployment for one year or less generally does not affect PM sensor performance. However, multi-year deployments may affect PM sensor performance (deSouza et al., 2023). In addition, prior research (Tryner et al., 2020) and Ecology evaluations have shown that exposure to high concentrations of PM degrades their performance over time.

1.5. Collocation-correction process

Unlike regulatory PM monitors that can be periodically calibrated, PM sensors cannot be adjusted. This is because PM sensors don't respond to the calibration gases used to calibrate nephelometers (CO_2 and Suva®) (J. R. Ouimette et al., 2022).

In lieu of calibration, Ecology runs PM sensors alongside a regulatory monitor to see how their data correlate in a process we call "collocation." By comparing the data from the sensor to the regulatory monitor, we can determine whether the sensor is operating within defined quality criteria. Sensors that do not meet criteria are not used.

Additionally, sensor performance is evaluated regionally. Pooled sensor values are compared to regulatory values through linear regression to determine a region-specific correction factor.

Raw sensor values are multiplied by this adjustment factor to improve accuracy. We call this data adjustment process “correction.”

The collocation-correction process elevates Ecology’s PM sensor measurements closer to the level of regulatory PM monitoring.

1.5.1. Continuous subset collocation strategy

To organize the PM sensor collocation process, Ecology adapted the “Continuous Subset Strategy” from the EPA’s Enhanced Air Sensor Guidebook. Under this approach, we first collocate PM sensors at reference sites equipped with a FEM Beta Attenuation Monitor (BAM) configured for the corresponding size fraction ($PM_{2.5}$ or PM_{10}) for a minimum of 30 days. Figure 1-1 shows $PM_{2.5}$ and PM_{10} sensors collocated with BAMs.

Collocation sites are chosen to be representative of the meteorological conditions and PM composition of regions within Washington State. RH and temperature readings from each sensor are recorded, as well as meteorological conditions from the nearest weather station for the duration of collocation.

The 30-day duration of collocation balances the opposing needs for exposure of PM sensors to a range of ambient concentrations and for quick deployment to host sites. If a sufficiently diverse range of concentrations is not observed in 30 days, collocation may continue for longer.

The Air Sensor Calibration & Repair Specialist and the Quality Assurance Coordinator use 1-hour and 24-hour averaged data to evaluate sensor performance with a consistent set of statistical metrics, as described in section 1.5.3, with a focus on inter-sensor variability. Sensors not meeting performance standards undergo repair or replacement. A sensor must pass a 30-day collocation before deployment.

After successful evaluation, sensors are deployed to solo monitoring sites within the surrounding area. A subset of sensors remains collocated with the reference instrument for correction development (see section 1.5.2) and performance monitoring over time. At least one sensor is always active at the collocation site for redundancy.

Following a year of solo deployment, sensors undergo another 30-day collocation period for performance reassessment. This verifies sensor performance during deployment and helps ensure data trustworthiness.

Figure 1-1: SensWA collocated with a BAM $PM_{2.5}$ (left) and two QuantAQ MODULAIR-PMs collocated with a BAM PM_{10} (right) at the Spokane – E. Broadway Ave. monitoring site.

1.5.2. SensWA correction methodology

This section focuses on the correction methodology for SensWA $PM_{2.5}$ sensors. Ecology will develop similar methods for QuantAQ MODULAIR-PM PM_{10} sensors in the future.

Ecology has three primary goals in that drive the SensWA correction approach:

- Aim for highest accuracy around 35 $\mu g/m^3$.
- Minimize misclassification by AQI category.
- Err on the side of overestimation, especially in higher AQI categories.

Ecology uses a linear regression model to derive a linear correction factor (slope) to adjust SensWA readings. Currently, an intercept of zero is applied because non-linear responses at low $PM_{2.5}$ concentrations (<10 $\mu g/m^3$) would result inaccurate intercepts. This approach avoids suppressing the slope's effect and improves accuracy.

While the SensWA reports readings for PM_1, $PM_{2.5}$, and PM_{10} on the EPM1, EPM25, and EPM10 channels respectively, Ecology has seen the best results using the EPM1 channel to measure $PM_{2.5}$. Therefore, the correction factor is derived from and applied to this channel.

For SensWA, Ecology uses the EPM1 data measured by the sensing element to estimate EPM25_corrected due to improved goodness-of-fit between EPM1 data and reference $PM_{2.5}$.

To derive correction factors for SensWA, Ecology correlates SensWA and reference $PM_{2.5}$ to identify the best-fit linear model. The slope of the linear model is the correction factor for SensWA. Ecology currently does not apply an intercept to SensWA data because we observed a non-linear response below 10 $\mu g/m^3$ of the Sensirion SPS30 sensing element resulted in unreasonably high intercepts. Setting intercept to zero was found to increase accuracy by preventing suppression of slopes caused by such intercepts. Ecology is in the process of developing more complex mathematical correction models in the future.

Ecology currently develops regional corrections by combining correlation data from multiple collocation sites that are in the same region of the state and expected to have similar airshed conditions. At this time, Ecology generally defines two seasons for SensWA correction based on predominant $PM_{2.5}$ source: wildfire smoke (late-spring to early-fall) and home-heating smoke (late-fall to early-spring). Ecology will continue to refine its regional and seasonal PM sensor correction approach in the future.

Currently, Ecology does not include RH and temperature in its correction equation for SensWA. SCAQMD field and laboratory studies (https://www.aqmd.gov/aq-spec/sensordetail/sensirion---sps30-eval-kit), as well as Ecology observations in the Washington Network, show a minimal effect of RH and temperature on Sensirion SPS30 sensing elements. However, SensWA records RH and temperature measurements to potentially refine the correction equation in the future.

1.5.3. Statistical evaluation

Ecology evaluates SensWA performance by comparing to collocated FEMs (a BAM 1020 or 1022) following recommendations from the EPA's air sensor performance target report for $PM_{2.5}$ (Clements et al., 2022).

Statistical metrics are calculated separately for:

- **24-hour averages:** Consistent with the reference monitor and EPA recommendations for $PM_{2.5}$ sensor evaluation.
- **1-hour averages:** While 1-hour metrics may not always meet 24-hour targets due to inherent variability in short-term measurements, they allow for analysis of sensor response time to changing concentrations.
- **Wildfire vs. non-wildfire periods:** Separating data by wildfire influence helps isolate the impact of these events on sensor performance.

Key metrics and quality criteria include:

- **Bias and Linearity:** Ordinary least squares (OLS) regression is used to assess bias (intercept, ±5 µg/m^3) and linearity (slope, 1 ± 0.35) between SensWA and reference measurements. The coefficient of determination ($R^2 \geq 0.70$) indicates how well the linear regression fits the data.
- **Data Completeness:** High data completeness (>90%) is important for comparison. Low data completeness could indicate an issue with sensor health.
- **Error Metrics:** Root Mean Squared Error (RMSE; ≤ 6 µg/m^3) and Normalized Root Mean Squared Error (NRMSE; ≤ 30%) quantify the absolute and relative magnitude of errors between SensWA and reference data. Mean Absolute Error (MAE; ≤ 6 µg/m^3) and Mean Absolute Percentage Error (MAPE; ≤ 30%) are also calculated.

Ecology uses EPA's performance targets for bias, linearity (slope, intercept, R^2), and data completeness as pass/fail criteria for 24-hour collocation data. However, exceeding error metric targets (RMSE, NRMSE, MAE, MAPE) does not automatically disqualify a SensWA.

During periods of high concentrations, such as wildfire smoke events, it is preferable to use normalized metrics (NRMSE, MAPE) because larger absolute (RMSE, MAE) errors are common.

Ecology also evaluates the accuracy of corrected SensWA data in reporting the same AQI category as the reference monitor. This helps the data displayed on Ecology's monitoring site and EPA's fire and smoke map accurately reflect health conditions.

1.5.4. Collocation exceptions

PM sensors in the Ecology network require a 30-day collocation with a BAM 1020/1022 before deployment. However, exceptions are allowed with prior approval by the Quality Assurance Coordinator in consultation with the Air Sensor Calibration & Repair Specialist and Air Monitoring Coordinator. For example:

- **Collocation with a nephelometer:** Ecology evaluates SensWA comparability to nephelometers for $PM_{2.5}$ monitoring through collocations in the Washington Network. If collocation shows SensWA can achieve comparable data quality to nephelometers at a monitoring site over a year, SensWA may replace the nephelometer at that monitoring site. In such cases, the Air Sensor Calibration & Repair Specialist and Quality Assurance Coordinator will correct SensWA data based on the site-specific nephelometer collocation, as well as regional BAM collocations. Data from SensWA collocations with nephelometers may also be used, alongside data from SensWA collocations with BAMs, in calculating regional correction factors if no BAM is present within the airshed of interest.
- **Response to isolated or emergent events, including wildfires**: The Air Sensor Calibration & Repair Specialist and Quality Assurance Coordinator will determine the proper correction factor to apply based on data from the nearest and most representative collocation. Without prior collocation, a SensWA should not be deployed for temporary monitoring longer than six months.

2. Operator Considerations

2.1. Coordination with Air Sensor Calibration & Repair Specialist

Before you travel to a PM sensor collocation or host site, or for first setup or later maintenance, contact Air Sensor Calibration & Repair Specialist to confirm your plans.

Before you leave the sensor site, or after first setup or later maintenance, do the following:

- Confirm the indicator light on the front of SensWA or MODULAIR-PM shows a slow breathing cyan light. For the SensWA, confirm the secondary indicator light is not flashing yellow (indicates insufficient power supply).
- Contact Air Sensor Calibration & Repair Specialist to confirm data transmission or to troubleshoot.

2.2. Equipment & supplies

Operators should carry the following supplies to install and support PM sensors:

- Zip ties or pole mount kit (supplied by Calibration & Repair Laboratory)
- Alternative mounting hardware (screws, nuts, bolts, washers) (Optional)
- Various hand tools (flat and Phillips head screwdrivers, hexagonal wrenches)
- Battery-powered drill
- Cotton-tip applicators
- Rubbing alcohol
- Lint-free lab wipes
- Wire cutters, scissors, or other tool to cut zip ties

2.3. Tracking in Microsoft Teams

The Air Quality Program uses Microsoft Teams (“ECY-AQ Air Sensors”) as the repository for sensor inventory tracking. The Air Sensor Calibration Repair Specialist must ensure that the sensor inventory, testing, and location information kept in the “SensWA Tracking” and “ModPM Tracking” list tabs are updated weekly. Operators should review inventory tracking systems regularly, preferably weekly on Monday morning. Operators should notify Calibration & Repair Laboratory staff via email when sensor inventory tracking system inconsistencies are found. Information tracked in the “SensWA Tracking” and “ModPM Tracking” list tabs includes:

- Identification and serial numbers
- Location
- Installation date
- Zero testing date
- Status

2.4. Data quality control

2.4.1. Data ingest

Incoming data is reviewed by operators at least weekly. Additionally, Ecology scripts process each 10-minute dataset to apply minimal QC checks and fill missing values.

2.4.1.1. SensWA automated checks

Values of "nan" are replaced with a missing flag of -9.9 for all parameters, aside from temperature, which is replaced with "-99".

If instead of a timestamp reports a value of UNIX__TIME, then the 10-minute data set is not imported. This sometimes occurs when a device first powers up and all 10 minutes of data will look the same with default values.

Region and season-specific correction factors are applied to the EPM1 and EPM1_2 channels. Corrected values are saved in the database as EPM25_corrected and EPM25_2_corrected. EPM25_2 corrected is used for comparison validation and as a backup for public display.

To identify issues with sensors, values from each sensor channel (EPM_25_corrected and EPM25_2_corrected) are compared. If the values differ significantly, it indicates that one has failed or started to drift. The following checks are applied to compare the EPM25_corrected and EPM25_2_corrected channels:

- If the lesser value is > 35 ug/m^3, and the values are outside of a 1.5x multiplier of each other, invalidate both.
- If the lesser value is between 10 and 35 ug/m^3, and the values are outside of a 2x multiplier of each other, invalidate both.
- If the lesser value is < 10 ug/m^3, and the values are outside of a 3x multiplier of each other, invalidate both.
- If the lesser value is <5 ug/m^3, do not invalidate any data.

If EPM25_corrected or EPM25_2_corrected channel data are reporting >10% invalid, data polling is turned off. EPM25_corrected or EPM25_2_corrected can be reported without comparison checks but should not be used long term (1 week).

2.4.1.2. MODULAIR-PM automated checks

Fog particles can interfere with the counting of coarse particles by the optical particle counter in the MODULAIR-PM, which leads to inaccurate measurements. Based on field studies, QuantAQ found that fog is most likely to form when the difference between the measured ambient temperature and the dew point, referred to as "dew point spread", is less than 3.75°C. Following QuantAQ guidance, Ecology invalidates data when the following two conditions are met:

1. The dew point spread is less than 3.75°C
2. The coarse particle mass concentration (PM_C) exceeds 200 µg/m^3

Ecology also follows QuantAQ guidance to smooth the data using a rolling maximum over an eleven-minute window to prevent instantaneous drops in flagged data. More information on data filtering for fog interference in MODULAIR-PM, see QuantAQ documentation (https://zenodo.org/doi/10.5281/zenodo.10793533).

MODUAIR-PM does not have paired identical sensing elements and so the invalidation by comparison method used for SensWA does not apply.

2.4.2. Operator data assessment

Operators perform preliminary review and validation of PM sensor data. Operators should review data promptly, preferably weekly on Monday morning. Operators should notify Calibration & Repair Laboratory staff via email when invalid data or other issues are found.

Considerations when assessing PM sensor data quality include:

- Correlation with nearby PM monitors (FEM, nephelometers, and PM sensors).
- Agreement of PM sensing elements paired in unit.
- Data completeness.
- The data quality indicators in Table 2-1.

Table 2-1: Indicators of poor-quality PM sensor data

Indicator	Causes
Progressively lower PM concentrations measured over time.	- Deposited PM on the optics of the sensing element reduces scattering signal intensity. Most common after high PM concentration events.
Odd patterns, especially sporadic periods of high concentration spikes inconsistent with ambient concentrations.	- Bug or spider infestation in sample airflow. - Water damage to PM sensing element or circuit board from exposure to precipitation or high humidity. - Resuspended PM previously deposited on the walls of the airpath during high concentration periods.
Increased noise in data.	- Water damage to PM sensing element or circuit board from exposure to precipitation or high humidity.
Data transmits, but all concentrations are zero.	- Loss of power to PM sensing element airflow fan or scattering laser, due to fault in circuit board electronics. - Obstructed sample airflow.
Missing data.	- Lost connection to cellular network, either due to loss of power or poor signal.

After review by operators, the Air Sensor Calibration & Repair Specialist and the Monitoring Coordinator, QA will conduct the final data validity evaluation. QA will use electronic logbook entries (Figure 2-1) in their final review. Operators document site activities and ensure that all required QC and maintenance activities occur as required by this procedure.

2.5. Maintenance

Good maintenance processes can help maximize PM sensor performance and longevity. PM sensors in the Ecology network are maintained on a quarterly and annual schedule by operators and the Air Sensors Calibration & Repair Specialist.

2.5.1. Quarterly maintenance

Operators must visit the site quarterly and perform maintenance according to the following steps:

1. Wipe any accumulated dirt off the outside of the enclosure.
2. Inspect the inlets for spider webs, bugs, and wasp nests, as well as water damage. Wipe the sensor inlet clean.
3. (SensWA only) Open the enclosure to ensure all internal wires are connected and secure, including the:
    - Cell antenna
    - Sensirions (2x)
    - RH&T sensor
    - USB power
4. Inspect internals for spider webs, bugs, and wasp nests, as well as water damage.
5. Wipe the O-ring of the front panel and the internal edges of the main body. Ensure front panel seal is watertight.
6. Ensure the secure attachment of the PM sensor to its support.
7. If powering the PM sensor by solar:
    a. Wipe the Voltaic solar panel clean.
    b. Confirm external power connections are secure and inspect for water damage.
    c. Open the battery enclosure and inspect for wear. Note the battery charge level and replace with a fully charged backups if below 50%.
    d. Adjust the angle of the solar panel according to season, as shown in Figure 4-2.

Operators should record in EnvistaARM the activities conducted during their site visit and any notable observations (spider webs, bugs, wasp nests, water damage, loose electrical connections or mounting, low batter level if solar powered). See Figure 2-1 for an example logbook entry.

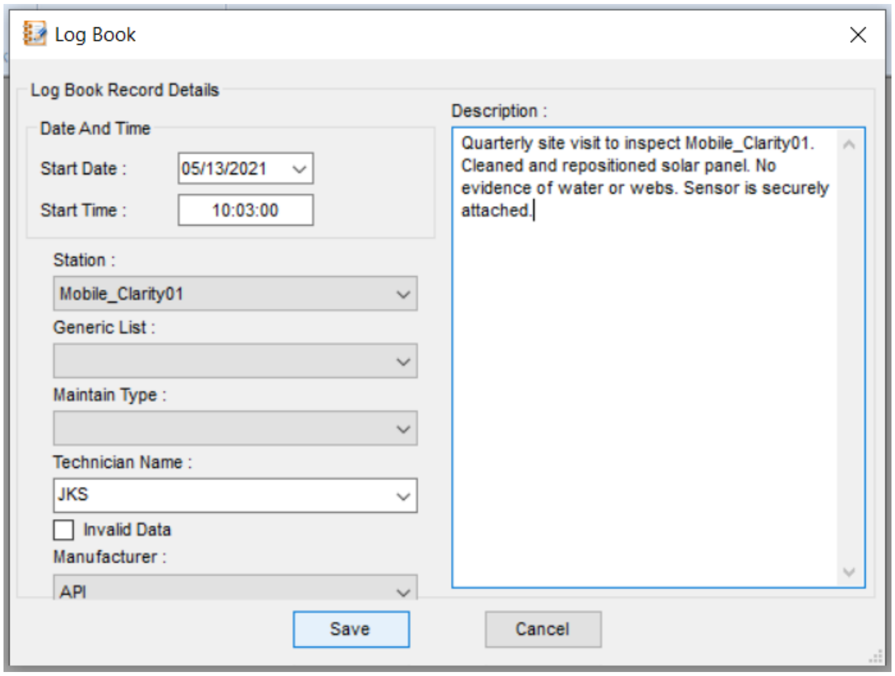

Figure 2-1: Example logbook entry for quarterly site visit using EnvistaARM.

2.5.2. Annual maintenance

The Air Sensor Calibration & Repair Specialist will perform 12-month maintenance in the Calibration & Repair Laboratory. Operators must ship the sensor to the Calibration & Repair Laboratory annually. The Calibration & Repair Laboratory will keep records of 12-month maintenance completed. This maintenance consists of the following steps:

1. Clean the inside and outside of enclosure, paying special attention to airflow path.
2. Check integrity of seals on cable gland and air vent, looking for signs of degradation or water intrusion. Tighten as needed and replace if compromised.
3. Clean bug screens:
    a. Remove visible dirt and cobwebs with a brush.
    b. (SensWA only) Re-apply glue if not secure or degraded.
    c. (SensWA only) Replace screen if any holes are present.
4. Clean PM sensor airflow:
    a. Clean visible dirt and cobwebs with a brush.
    b. Check for signs of water damage.
    c. Blow clean with compressed air.
5. (SensWA only) Clean and replace SPS30 PM, temperature, and RH sensing elements if significantly dirty, water damaged, or deployment data shows reduced performance. See Section 5.1 for description and location of these elements.
6. (SensWA only) Connect SPS30 sensing elements to computer with Sensirion Control Center software installed using USB connectors.
    a. Enact “Manual Cleaning” function. This function runs internal fan at maximum speed for ten seconds. Repeat five times.
    b. Leave SPS30 sensing element connected to computer for zero test (next section).

2.5.3. Annual (12-month) zero test for SensWA

After annual maintenance, the Air Sensor Calibration & Repair Specialist will perform a zero test of the Ecology SensWA PM sensors. To do so, place the PM sensor (or the Sensirion SPS30 sensing element) in a vented chamber filled with particle free air for at least 240 minutes (4 hours).

The Calibration & Repair Laboratory keeps records of all annual (12-month) zero tests completed.

2.5.4. Annual (12-month) collocation

After annual maintenance (and zero test for SensWA), the Air Sensor Calibration & Repair Specialist will collaborate with operators to arrange the annual >30-day collocation test at a designated reference site before deployment at a host site. Operators will collocate PM sensors with either a $PM_{2.5}$ (for Ecology SensWA) or PM_{10} (for QuantAQ MODULAIR-PM) BAM, 1020 or 1022, for a minimum of 30 days. The Air Sensor Calibration & Repair Specialist and the Quality Assurance Coordinator will use 1-hour and 24-hour averaged data from the collocation of PM sensors to evaluate performance under a consistent set of statistical metrics measuring precision and accuracy, with a focus on inter-sensor variability. PM sensors not meeting performance standards will be fixed by operators onsite if possible or returned to the Air Sensor Calibration & Repair Specialist.

The Calibration & Repair Laboratory keeps records of all annual (12-month) collocations completed.

To reduce variability during collocation, operators should install the PM sensors near the BAM 1020 or 1022. Ideally, operators should install PM sensors and BAM 1020 or 1022 within ten meters (30 feet) of each other, with inlets should at similar height. No other structure or device should block the movement of air around the PM sensor.

3. PM Sensor Site Setup

3.1. Siting guidance

PM sensors should be installed according to the guidelines in Ecology's Air Monitoring Site Selection and Installation Procedure to the extent possible. Specifically, Section 5 lists considerations for site selection, power and safety requirements, and key factors in choosing a location.

Additionally, PM sensors should be installed in a location with unrestricted airflow, according to the following guidelines:

- Install PM sensors as far as possible from obstructions, including trees and buildings.
- A pole, fence, or railing offers the least restriction of airflow.
- If you cannot attach to a point with unrestricted airflow, use the outside corner of a building with 270 degrees of unrestricted airflow.
- If prior options are unavailable, install on a flat wall with 180 degrees of unrestricted airflow (both horizontal and vertical).
- Never install PM sensors inside corners where two walls meet or under large eaves or awnings.
- Prioritize including prevailing winds where they can be determined for the site.

3.2. Site information management in Microsoft Teams

The Air Quality Program uses Microsoft Teams ("ECY-AQ Air Sensors") as the repository for sensor site and inventory information. Station operators must make a Microsoft Forms submission through the "Submit Site Info" tab on the "ECY-AQ Air Sensors" Teams site whenever setting up a sensor site. See Table 3-1 for an example "Submit Site Info" response. The Air Sensor Calibration & Repair Specialist and the Air Monitoring Coordinator transfer the site information submitted by site operators to the "Site Info" list tab on the "ECY-AQ Air Sensors" Teams site where it is stored for reference.

In addition to submitting site information, operators must submit site photos of the eight compass cardinal points (N, NE, E, SE, S, SW, W, NW), to the "Submit Site Photos" tab on the sensor Teams site.

Table 3-1: Example response for the "Submit Site Info" in Ecology's Microsoft Teams site information management system.

Question	Response
Ecology region or local clean air agency name	Northwest Region
Primary site operator	Kate Miller
Other operators to notify in case of issues	Greg Crider, Matt Bechle, Jenny Li
Pollutant	PM2.5
Expected installation date	5/16/2024
City or town	Seattle, Beacon Hill neighborhood
Facility name	El Centro De La Raza (ECDLR)
Facility owner (e.g. school district, fire department, local government)	El Centro De La Raza
Street address	2524 16th Ave S, Seattle, WA, 98144
Latitude, longitude	47.3450, -122.1842
Primary contact at site (name, title, telephone number, email).	*EXAMPLE*, Facility Manager, *EXAMPLE@EXAMPLE.ORG*
Please describe the purpose of this new sensor, why you selected this area for a sensor installation, and other context about this community and its air pollution concerns.	CCA overburdened community (South Seattle); Site fits need for expanded monitoring in the central portion on Beacon Hill community
Dominant PM sources in the area	Road traffic, home heating, commercial restaurants
Expected seasonal patterns	Wildfire summer, home heating winter
Spatial scale of representativeness	Neighborhood (0.5 - 4 km) *(Most common scale for $PM_{2.5}$ monitoring)*
Monitoring objective(s)	Population exposure: Sites located to measure typical concentrations in areas of high population density. *(Most common objective for $PM_{2.5}$ monitoring)*
Electrical needs	Solar panel and battery needed
Site security	Fenced area
Is adequate cell coverage available? (AT&T or T-Mobile)	Yes
Please describe location relative to any obstructions (e.g. walls, trees), potential local sources (e.g. dust, idling vehicles), and any unique site characteristics.	Located in a fenced edge of a garden with no tree obstructions. Large main office building about 57ft (16m) to the east

4. Solar Power

A Voltaic solar power system can power Ecology SensWA or QuantAQ MODULAIR-PM in locations without access to a fixed power outlet. This system is assembled by the Air Sensors Calibration & Repair Specialist, and consists of the following components:

- Voltaic 20 W solar panel with mounting bracket
  - For non-winter smoke response deployments, use one 20 W solar panel
  - For year-round deployments, use two 20 W solar panels and adjustable mounting bracket
- Weatherproof battery enclosure with screw-on front panel and cable gland port.
- Figure 4-1shows the internal components of the battery enclosure, which includes:
  - Voltaic red extension cable (connects to solar panel externally, feeds through cable gland, connects to splitter internally)
  - Voltaic red splitter cable (connects extension cable from solar panel to two batteries inside enclosure)
  - Voltaic V75 USB batteries attached to the mounting plate and each other (charged to full capacity by Calibration & Repair before shipment)
    - For non-winter smoke response deployments and most year-round deployments, use two Voltaic V75 USB batteries
    - For year-round deployment in locations that are colder or receive less sunlight during winter (e.g., further north, obstructed by dense trees or surrounding mountains), use four Voltaic V75 USB batteries
  - Black USB splitter(s) that connects two (or four) batteries together for USB power, with receptacle to plug in sensor power embedded in cable gland
    WARNING: Do not plug USB into battery packs prior to setting up solar panels. Doing so will slowly drain the batteries
- Mounting hardware (high strength zip ties, hose clamps, screws, nuts, bolts, washers)
- Backup of 2 x Voltaic V75 USB batteries and charging cables (operator responsibility to keep charged to full capacity)

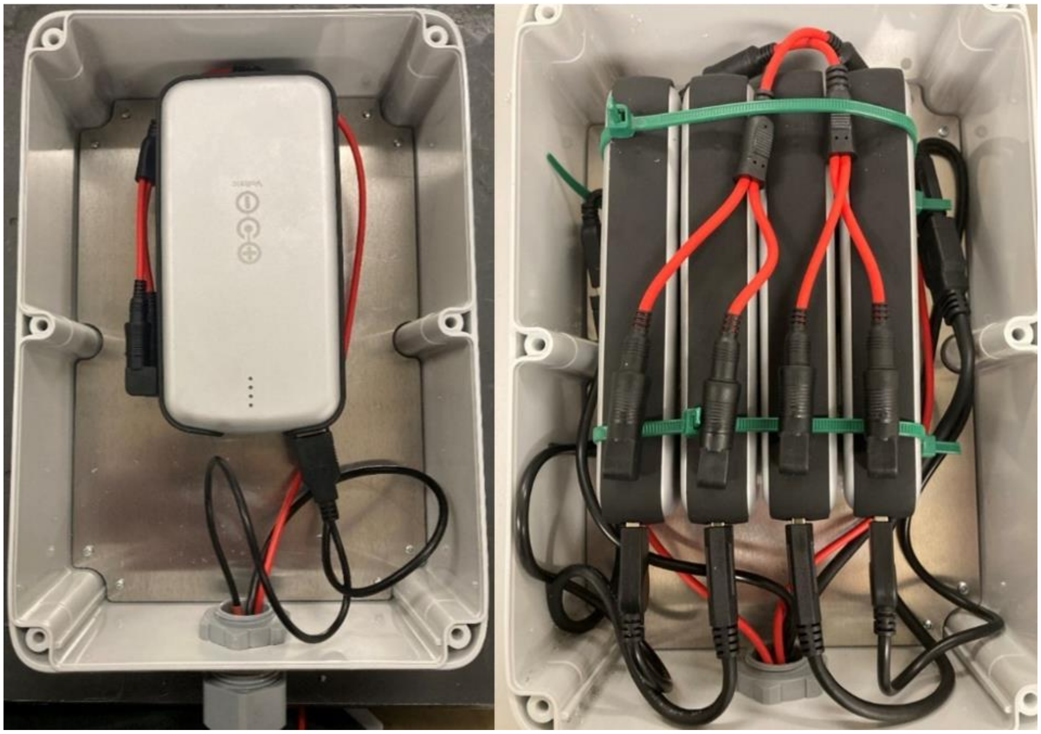

Figure 4-1: Voltaic battery enclosure with two (left) and four (right) V75 USB batteries.

Operators should follow these steps to set up the Voltaic solar power system for a SensWA or MODULAIR-PM:

1. Ensure you have fully charged the Voltaic V75 USB batteries (two for wildfire seasonal, four for year-round) inside the enclosure before going to the monitoring site. You may have to remove them from the enclosure to charge. The batteries charge using USB-C.
2. Complete the electrical connections inside the battery enclosure after you arrive at the site but before mounting.
3. When mounting, orient the Voltaic solar panel to face true south to maximize sun exposure. Changing the mounting angle seasonally maximizes sun exposure (Figure 4-2). The mounting angle of the solar panel can only be adjusted on the year-round system.
4. Mount the Voltaic solar panel and bracket securely to a pole, railing, or weighted tripod stand, using high strength zip ties or hose clamps. Alternatively, mount with screws directly into a pole, railing, or wall. Be sure this mounting is secure, and the tripod is weighted down with cinder blocks. The solar panel can act as a sail in the wind.
5. Mount the battery enclosure and bracket securely to a pole, railing, or weighted tripod stand, high strength zip ties or hose clamps. Alternatively, mount with screws directly into a pole, railing, or wall.
6. Securely connect the power cable connectors between the Voltaic solar panels and battery enclosure (red cables), and between the PM sensor and battery enclosure (black USB male from SensWA into USB female on underside port of battery enclosure).

For year-round deployments using the adjustable mounting bracket, operators should adjust the tilt angle quarterly according to Figure 4-2. See Figure 4-3 for a picture of SensWA with single 20W panel Voltaic solar power systems mounted directly to a utility pole in Winthrop, WA, and on a tripod stand. Note that the solar panel is installed on top, followed by the SensWA, and the battery enclosure on bottom.

Operators must obtain permission from property owners and utility companies before mounting to an existing structure or utility pole. If mounting to a tripod, weight the bottom with securely attached cinder blocks or bolt to an existing platform.

Optimum Tilt of Solar Panels by Month

Figures shown in degrees from vertical

Jan	Feb	Mar	Apr	May	Jun
27°	35°	43°	51°	59°	66°
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
59°	51°	43°	35°	27°	20°

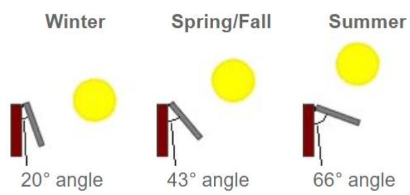

Image credit: http://www.solarelectricityhandbook.com/solar-angle-calculator.html

Figure 4-2: Optimum tilt of solar panels by month.

Figure 4-3: SensWA with solar power mounted to a utility pole (left) and year-round and a non-penetrating stand (right).

5. Ecology SensWA

5.1. Instrument layout

5.1.1. External

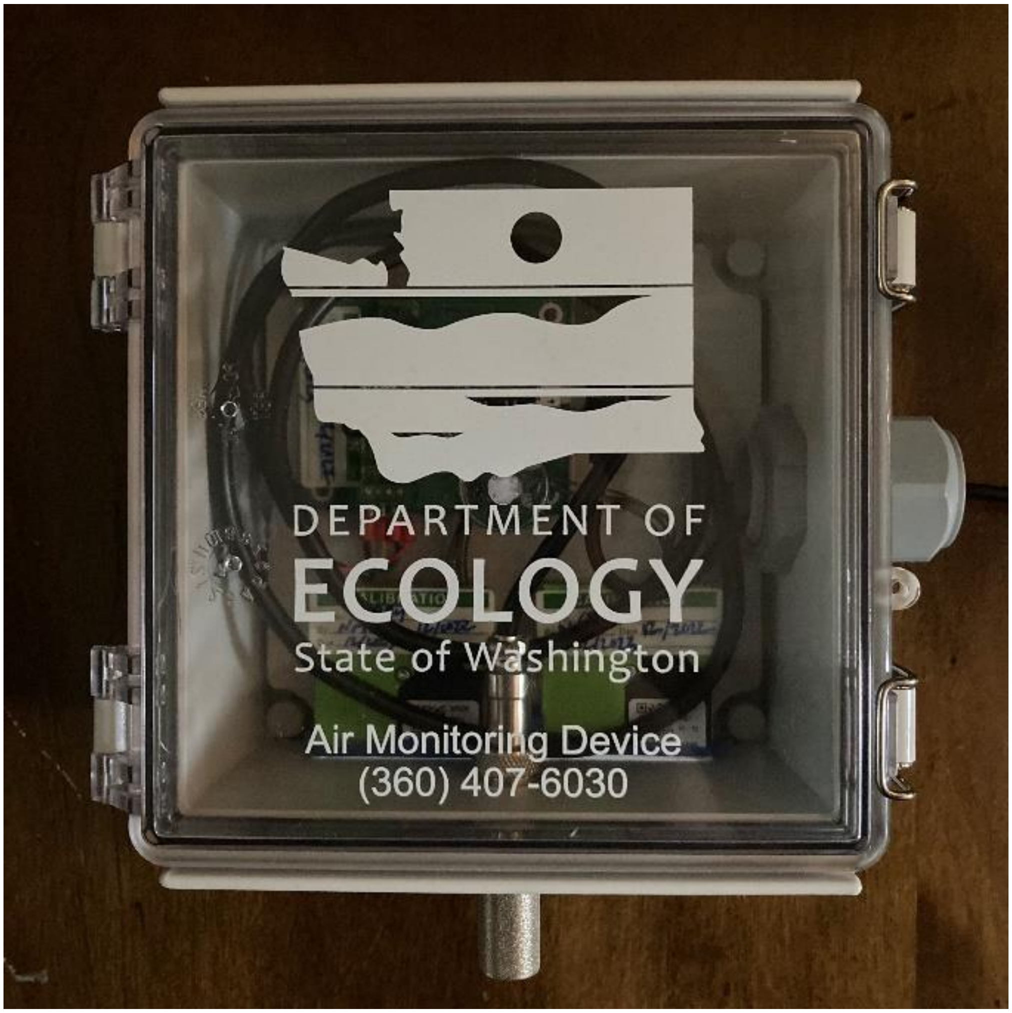

Figure 5-1: SensWA enclosure.

For ambient monitoring, mount the SensWA with the relative humidity and temperature (RH&T) probe and inlets on the bottom, as pictured in Figure 5-1. The bottom of the SensWA is pictured in Figure 5-2. You can see the following components externally on the SensWA:

- The cylindrical aluminum sintered RH&T probe (Adafruit Industries, SHT-30) protrudes from the center-bottom of the SensWA.
- Next to the RH&T probe on bottom of the SensWA are two rectangular holes that allow airflow to the two Sensirion PM sensing elements. A bug screen covers these holes. The sensing elements have an aluminum face with sample air intake and exhaust flow cutouts visible behind the bug screen.

- The grey power cable gland on the right side supplies a watertight entry for the power and data cable into the SensWA interior.
- The air vent on the left side helps prevent condensation inside the SensWA and normalizes internal conditions with ambient, while preventing bugs or spiders from entering.

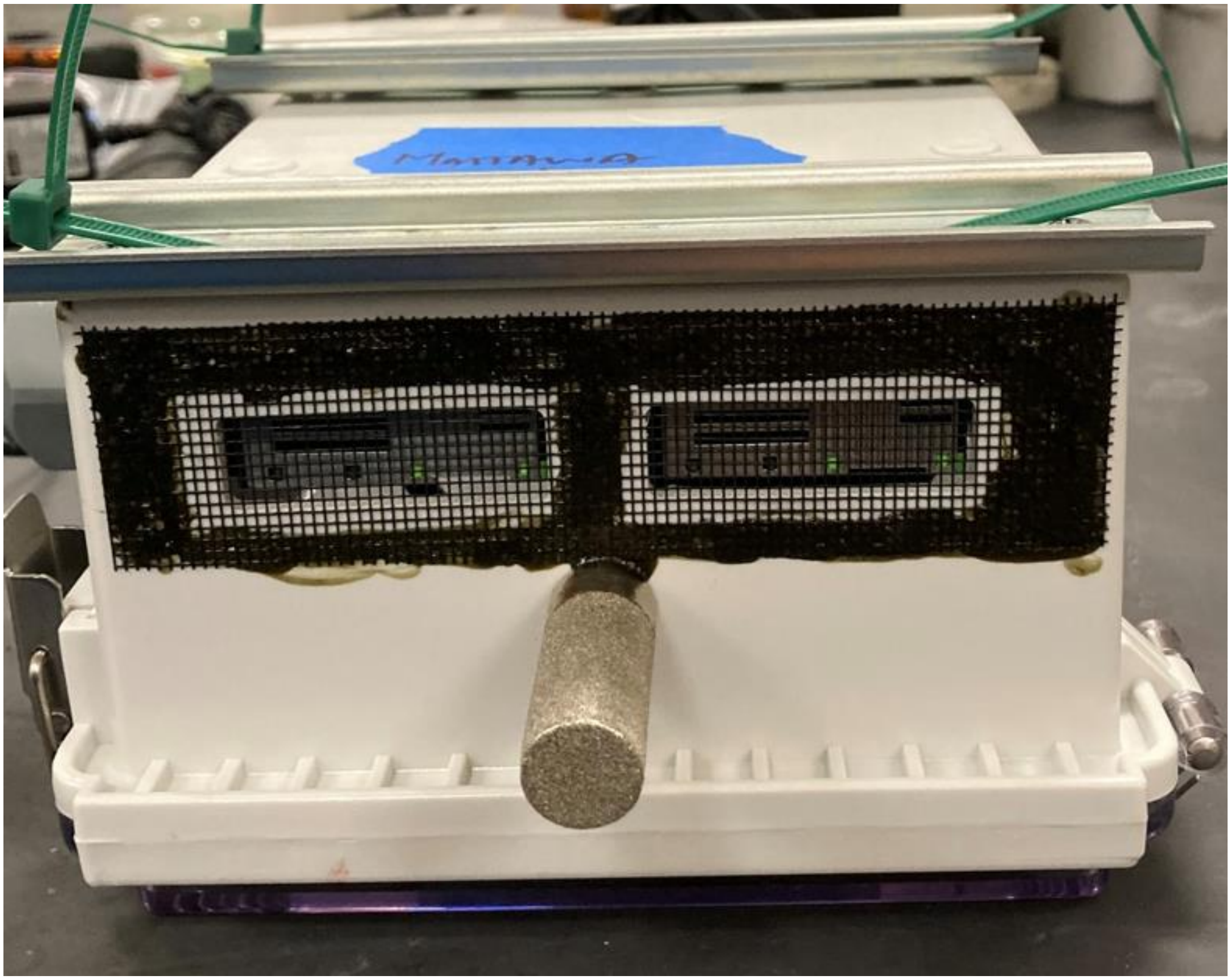

Figure 5-2: Bottom face of the SensWA enclosure.

5.1.2. Internal

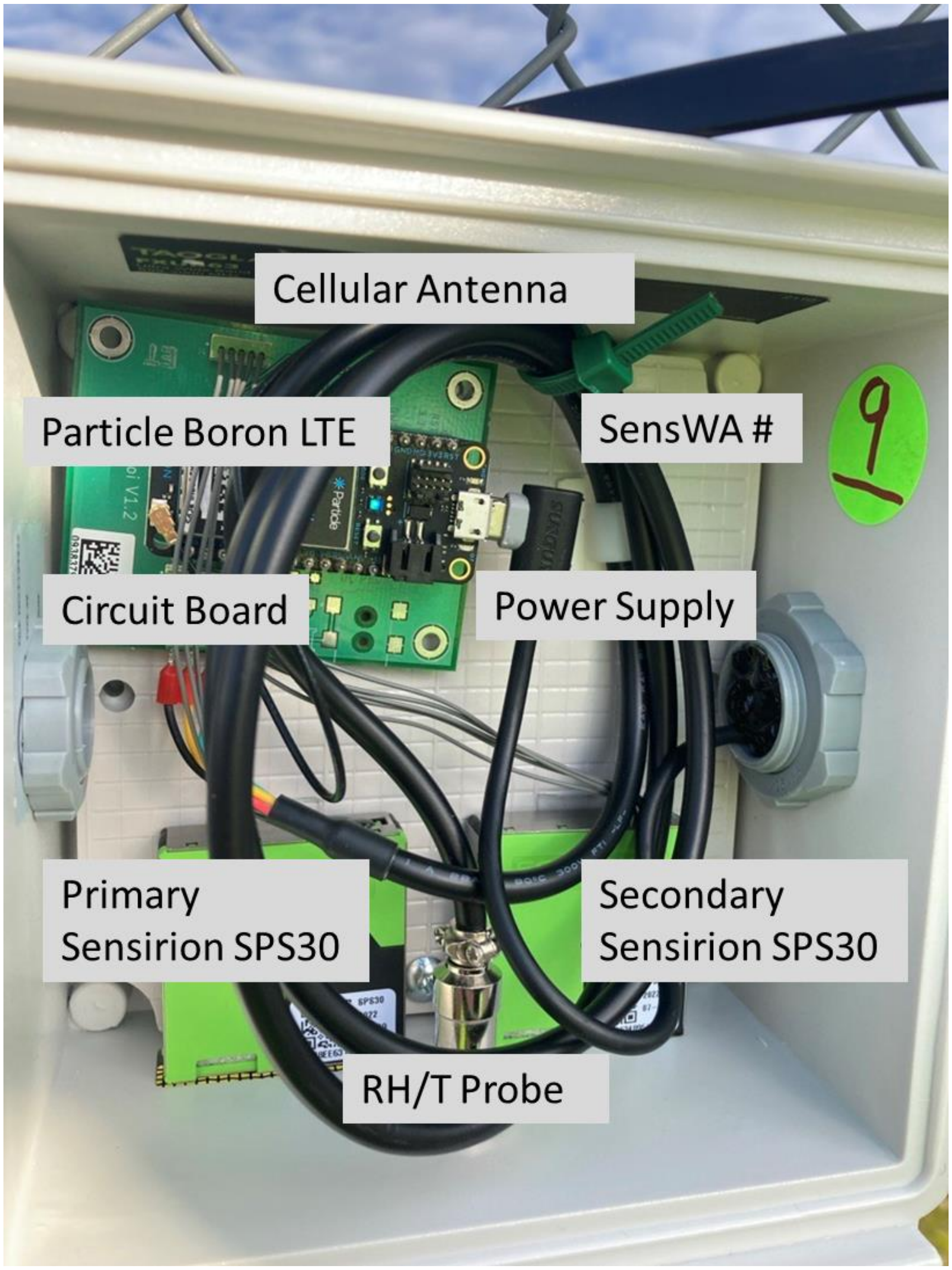

Figure 5-3: SensWA internal components.

Internal components of the SensWA are pictured in Figure 5-3, and include:

- **Particle Boron LTE communication board (Boron)**: transmits data via cellular service to the cloud from the SensWA. The Boron, which is black with blue lettering and a QR code, connects to an antenna and a USB power cord. The Boron also has an LED to show cellular communications status. After setup and plugin, make sure to note the status of the LED on the board. See section 5.2 for more details on the Boron.

- **Custom circuit board:** The Boron connects to a circuit board custom designed for the SensWA and manufactured by Screaming Circuits. Velcro connects the board to the mounting plate.
- **Cellular antenna (black rectangle):** Connects to the Boron by a thin black wire and gold circular connector. You will feel a snap into place when connecting to the Boron. Do not push too hard if misaligned as pins can easily bend. The antenna can easily disconnect from the Boron, causing cellular connection failure. Handle with care and ensure proper connection before closing the enclosure.
- **Aluminum RH&T probe:** connects by a thick black cable ending in four wires to the green connector on the circuit board. The four wires connect to the circuit board in the following order (left to right): black, yellow, green, red. A zip tie secures the excess RH&T probe wire in a loop and a clip attaches it to the mounting plate.
- **Two Sensirion SPS30 PM sensing elements (lime green squares):** Connect to the circuit board by sets of five thin grey cables with green connectors. The Sensirion SPS30 uses a polarized 660 nm laser to scatter light off particles and a photo diode detector to measure the scattered light. An internal fan provides airflow. Double-sided adhesive squares secure the Sensirion SPS30s centered on the rectangular airflow cutouts.
    - For more information on the SPS30, see Sensirion documentation.
    - For laboratory and field evaluation results, see South Coast Air Quality Management District's Air Quality Sensor Performance Evaluation Center results.

There are four stickers with tracking information on the inside of the enclosure:

- **SensWA ID number:** Green sticker in upper right corner.
- **Calibration tag:** Green and white sticker in the top left corner of the sidewall. Lists date of last annual maintenance.
- **Sensiron SPS30 calibration tag:** Green and white stickers on the interior of the front cover. Lists dates of last SPS30 zero tests.

5.2. Boron LTE cellular communications

The Boron LTE communications board (Figure 5-4) streams data via cellular signal and connects the SensWA to the Particle Device Cloud. There are two indicator lights, primary (circled in blue) and secondary (circled in orange) on the Boron that can be used to diagnose SensWA telecommunications status.

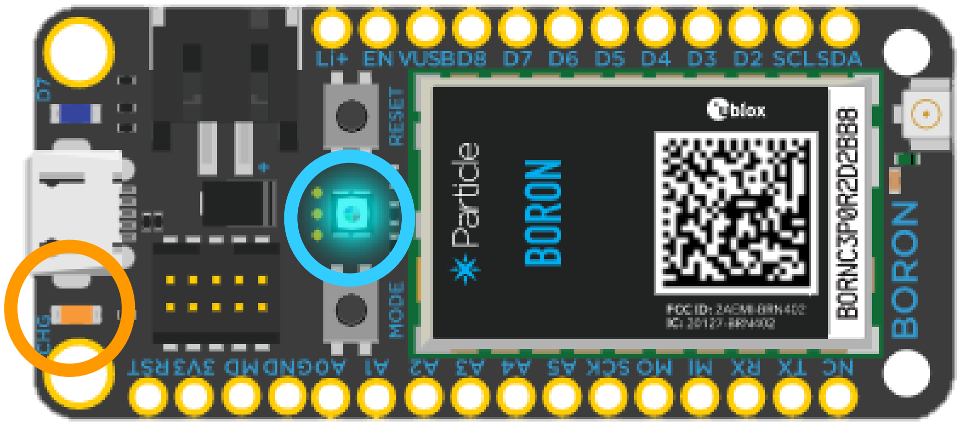

Figure 5-4: Boron LTE communications board.

5.2.1. Primary indicator light

- **Breathing Cyan:** Successful cellular connection to the cloud.
- **Rapidly Blinking Cyan**: Connecting to the cloud. This mode is typical when the device is first connected to a network, after it has just blinked green.
- **Blinking Green:** Trying to connect to cellular and not currently streaming data. If this state persists, contact Air Sensor Calibration & Repair Specialist.
- **Blinking Magenta (Red/Blue):** Loading an app or updating firmware. This mode may occur when the device is connected to the cloud for the first time.
- **Breathing Magenta (Red/Blue) *:** In safe mode and connected to the cloud but not running any application firmware. This mode is useful for development or troubleshooting.
- **Blinking Dark Blue*:** Listening Mode and awaiting further configuration.
- **Breathing White*:** Receiving power but the cellular module is off.
- **Blinking Red or Yellow*:** Variety of faults, bugs, or errors can cause red or yellow blinks. If this state persists, contact Air Sensor Calibration & Repair Specialist.
- **Solid Colors*:** Solid colors are rare, and usually the result of a bug or crash.
- **No Status LED*:** - A corrupted bootloader or physical damaged can cause your device status LED to not comes on when connected to power.

**If this state persists, contact the Air Sensor Calibration & Repair Specialist.*

5.2.2. Secondary indicator light

- **Flashing yellow:** The device is not receiving adequate power. This often results in reduced performance in the form of failed or inconsistent cellular connection.

5.2.3. Troubleshooting failed cellular connection

- Check the connection between cellular antenna and the USB power cord.
- Poor or inconsistent power supply reduces cellular signal strength. Use a different USB power block or plug the SensWA into different power outlets to try to improve power

supply. A USB multimeter, provided to operators by Air Sensors Calibration & Repair Specialist, can be helpful in diagnosing poor power supply.

- Tapping the MODE button on the Boron will blink out the bars of signal strength. More blinks show a stronger signal.
- SensWA may need to be deployed in areas with poor signal strength. Work with Air Sensor Calibration & Repair Specialist to find a solution, which may require an improved power supply or change in siting location.

5.3. SensWA installation

The best SensWA mounting configuration depends on the monitoring site characteristics. See section 3.1 for information on siting.

The Calibration & Repair Laboratory recommends high-strength zip ties or a pole mount kit (supplied by Calibration & Repair Laboratory) to secure the SensWA to a post, fence, or crossbar. Alternatively, operators can use mounting hardware to screw the SensWA directly to a post, crossarm, or wall. Figure 5-5 shows three SensWAs mounted with high strength zip ties.

If possible, avoid south-facing installations to reduce direct sunlight. Excessive sunlight through the clear front panel of the SensWA could degrade internal components over time. Consult with the Air Sensor Calibration & Repair Specialist if you have concerns about sun exposure at a site.

Figure 5-5: Pictures of SensWA mounted with high-strength zip ties.

Ensure all internal connections are secure before mounting the device. Once you mount the device, complete the following steps:

1. Plug in the USB power supply to a weatherproof power outlet.
2. Upon receiving power, the Boron LED indicator will flash green and eventually begin a sequence of slowly breathing cyan; this shows active cellular connection to the cloud server. This process will take longer when powering the device on in a new location. Typically, devices connect within 10 minutes, but may take 30 minutes or more.
3. The device will log data locally during this period and push it to the server once connected.

4. If the LED indicator does not eventually begin breathing cyan, the device has a cloud connectivity problem. Contact the Air Sensor Calibration & Repair Specialist.
5. Operators must notify the Air Sensor Calibration & Repair Specialist when deploying or relocating SensWA. The Air Sensor Calibration & Repair Specialist will configure the device, coordinate with the IT & Telemetry Unit to begin polling and web display and notify the Quality Assurance Coordinator to begin data review.

6. QuantAQ MODULAIR-PM

6.1. Instrument layout

6.1.1. External

For ambient monitoring, mount the MODULAIR-PM with the inlet on the bottom, as pictured in Figure 6-1. You can access the following components externally:

- On the bottom, you can see a square inlet that leads to the airflow path to the $PM_{2.5}$ and PM_{10} sensing elements. A metal bug screen covers the square airflow inlet.
- USB power connection on the bottom of the enclosure.
- On the right side of the enclosure, you can see the air vent for the exhaust airflow from the Alphasense PM_{10} sensing element.

Figure 6-1: MODULAIR-PM sensor, with optional solar panel.

6.1.2. Front panel

Access the front panel of the device by opening the lid of the enclosure. The panel supplies access to the ON/OFF switch, Menu, LED indicator, and the onboard micro-SD card. Figure 6-2 presents a photo of the front panel with components labeled. A Boron LTE communications board, which section 5.2 discusses in detail, powers the LED indicator light.

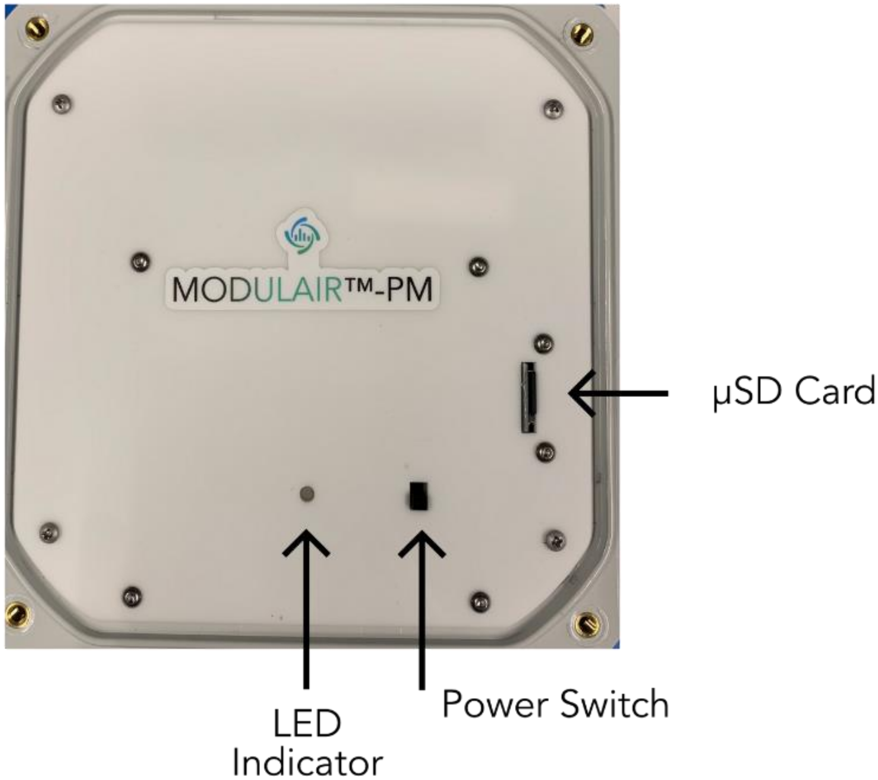

Image credit: https://docs.quant-aq.com/modulair-pm

Figure 6-2: MODULAIR-PM front panel.

6.1.3. Internal

Internal components are pictured in Figure 6-3 and Figure 6-4, and include:

- Core circuit board
- µSD circuit board
- RHTP sensor board
- Particle Boron LTE communications board
- Plantower $PM_{2.5}$ sensing element
- Alphasense optical particle counter PM_{10} sensing element

For laboratory and field evaluation results of the Alphasense OPC PM_{10} sensor, see South Coast Air Quality Management District's Air Quality Sensor Performance Evaluation Center results.

Consult with Calibrations & Repair Laboratory staff before touching any internal components.

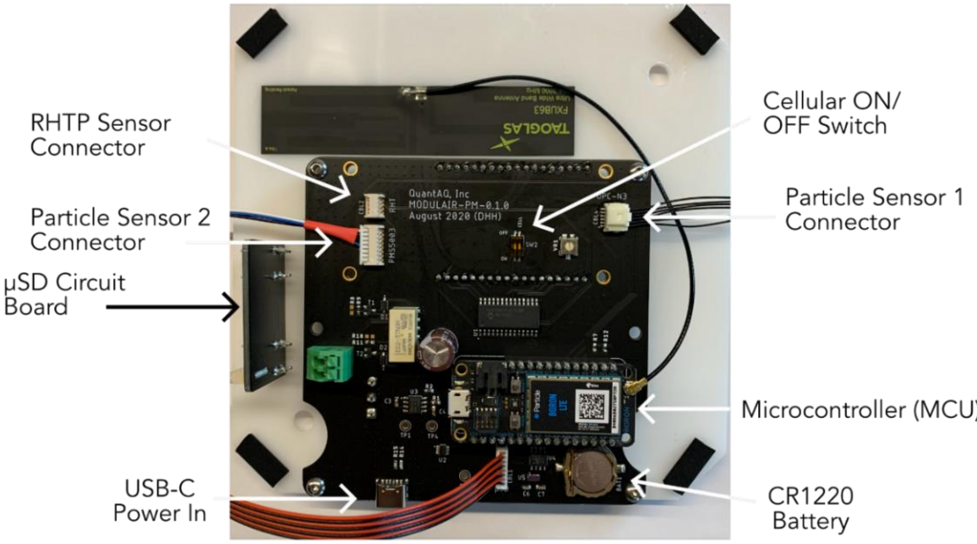

Image credit: https://docs.quant-aq.com/modulair-pm

Figure 6-3: MODULAIR-PM circuit board layout.

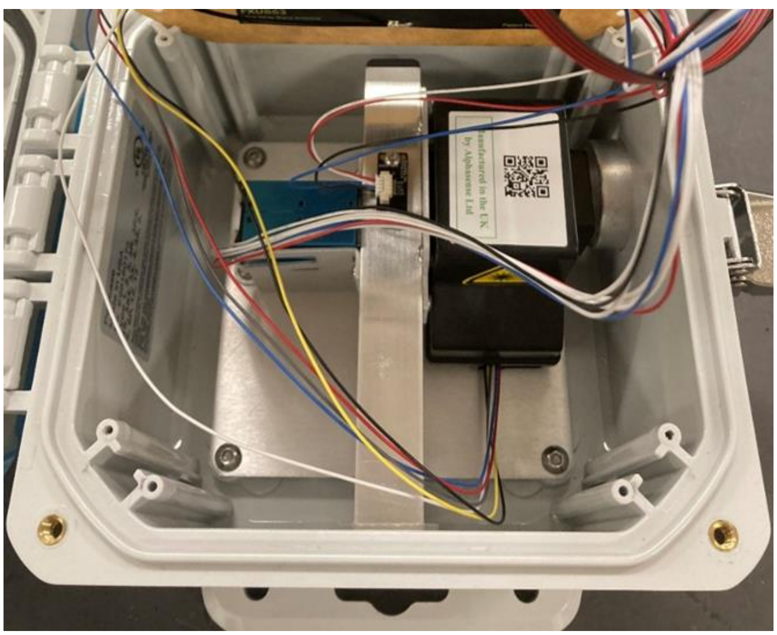

Figure 6-4: MODULAIR-PM sample flow path (silver, center), Plantower $PM_{2.5}$ sensing element (blue, left), and Alphasense OPC PM_{10} sensing element (black, right)

6.2. MODULAIR-PM installation

The best MODULAIR-PM mounting configuration depends on the monitoring site characteristics. See section 3.1 for information on siting.

The Calibration & Repair Laboratory ships the device with mounting flanges. Two stainless steel screws (included) secure the flanges to the back of the device. Each flange includes three slots for mounting hardware. See QuantAQ documentation for more info. The Calibration & Repair Laboratory recommends operators use high-strength zip ties or a pole mount kit (supplied by Calibration & Repair Laboratory) to secure the MODULAIR-PM to a post, fence, or crossbar. Alternatively, operators can screw the MODULAIR-PM directly to a post, crossarm, or wall. Contact the Air Sensor Calibration & Repair Specialist for help.

Once you mount the device, complete the following steps:

1. Turn the power switch to the OFF position, then plug in the power supply and plug the USB-C cable into the bottom of the device.
2. Connect the power cable to the device and to a weatherproof power enclosure, then flip the power switch to the ON position.
3. Upon receiving power, the LED indicator (Figure 6-2) will flash green and eventually begin slowly breathing cyan; this shows active cellular connection to the cloud server. This process will take longer when powering the device on in a new location. Typically, devices connect within 10 minutes, but may take 30 minutes or more.
4. The device will log data locally during this period and push it to the server once connected.
5. If the LED indicator does not eventually begin breathing cyan, the device has a cloud connectivity problem. Contact the Air Sensor Calibration & Repair Specialist.

Operators must notify the Air Sensor Calibration & Repair Specialist when MODULAIR-PM sensors are deployed or moved. The Air Sensor Calibration & Repair Specialist will configure the devices in the QuantAQ Cloud, coordinate with the IT unit to begin polling and web display, and notify the Quality Assurance Coordinator to begin data review.

7. Final Data Validation and Quality Assurance

The QA team performs final data validation in EnvistaARM. Data validation includes:

- Reviewing results from custom R and Python statistical analysis package.
- Using the EnvistaARM to review reports from operators.
- Using the EnvistaARM to review collected data for reasonability and comparability with other area monitors.
- Invalidating data collected during times when PM sensors run in error or outside QC acceptance limits.

QA staff evaluates data validity using a systematic criterion including comparability to collocated and nearby PM sensors, nephelometers and $PM_{2.5}$ monitors, as well as the results of quality control checks. QA staff manage final review and data validation.

For additional information on data validation, see Ecology's Data Validation SOP.

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