IS XXXXX : XXXX

*प्रारंभिक भारतीय मानक मसौदा*

आउटडोर और इनडोर वातावरण में पार्टिकुलेट मैटर के निर्धारण के लिए सेंसर आधारित उपकरण

*Preliminary Draft Indian Standard*

**PERFORMANCE SPECIFICATION OF SENSOR BASED INSTRUMENTS FOR MEASUREMENT OF PARTICULATE MATTER IN OUTDOOR AND INDOOR ENVIRONMENT**

ICS No. 13.040.20

© BIS XXXX

**B U R E A U OF I N D I A N S T A N D A R D S**

MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG

NEW DELHI 110002

*xxxx*  **Price Group**

Air Quality Sectional Committee, CHD 35

Foreword

**Introduction**

The market for sensor-based instruments for monitoring air pollution is growing tremendously due to the affordability and portability of such instruments. The low cost of these instruments makes it possible to use these in dense networks, which in turn give better spatial and temporal data. The fact that people from non-scientific community can use these instruments in their daily lives to monitor the air quality in their surroundings increase the attraction and demand of these instruments.

However, these instruments are not comparable to regulatory grade instruments in terms of accuracy and precision as they are prone to several interferences caused by atmospheric conditions. Researchers are working towards enhancing the performance of sensors and this technology has the potential to become a vital complementary technology to the regulatory monitoring. Some important facts about sensor technology:

* Sensor technology is very effective for capturing more detailed temporal and spatial variations
* With proper calibration methodology and protocol, and quality assurance and quality control processes in place, performance of such instruments can be enhanced
* Performance enhancement can also be achieved by improving sensor design and ensuring other elements like the algorithm, corrections (for temperature and relative humidity), instrument design, etc. complement the sensor
* It is an evolving field where continued research in the area of sensor application for environmental quality monitoring is taking place

*Preliminary Draft Indian Standard*

**PERFORMANCE SPECIFICATION OF SENSOR BASED INSTRUMENTS FOR MEASUREMENT OF PARTICULATE MATTER IN OUTDOOR AND INDOOR ENVIRONMENT**

# Scope

This standard prescribes performance requirements, sampling, and methods of test for sensor-based instruments used for indicative measurement of particulate matter (PM10 and PM2.5) in outdoor and indoor environment.

# References

# Terminology

## **Selectivity**

It is the ability of a sensor to identify the pollutant of interest from within a complex mixture of pollutants.

## **Sensitivity**

It can be defined as the minimum change in concentration for which a change in the sensor response is recorded.

$$S=\frac{∆R}{∆C}$$

where R is the sensor reading and C is the concentration of the target pollutant.

## **Response Time**

Time taken by sensor to measure and reflect the change in concentration of the pollutant(s) being measured.

## **Precision**

The degree of repeatability of measurement by a sensor/a group of identical sensors under identical set of conditions. This is often represented using standard deviation.

## **Accuracy**

It is the maximum difference between the actual value (measured using reference grade instruments) and sensor reading, and can be expressed either as percentage of full scale or in absolute terms. It is a combination of systematic error and random error.

## **Uncertainty**

## Bias from actual value estimated at 95% confidence limit.

## **Completeness**

The number of valid measurement data obtained in actuality from the sensor system compared to the number of measurements that were expected to be obtained under ideal conditions.

## **Detection Limit**

The minimum target pollutant concentration that can be measured by the instrument with a certain degree of confidence.

## **Duration of Measurement**

The time interval over which the instrument is programmed to measure and collect data of concentration of target pollutants.

## **Measurement Frequency**

The time interval between successive measurements. The number of measurements made in a given duration of measurement (**3.9**) can be calculated from this.

## **Range of Measurement**

The difference between the maximum concentration of target pollutant that an instrument can measure with acceptable degree of confidence and its detection limit.

## **Calibration**

Testing linearity of operation of sensor-based instruments at minimum 3 points (with respect to particle mass concentration).

## **PM10**

Inhalable particles, with diameters that are 10 micrometers and smaller.

## **PM2.5**

Fine inhalable particles, with diameters that are 2.5 micrometers and smaller.

## Operation Variability (Shankar Aggarwal)

# Application

Sensor-based instruments are not currently at par with regulatory grade instruments; thus, it is important that the measurement objective of the instruments be identified. The sensor-based instruments characterized in this standard shall not be used for regulatory reasons or policy making; they can be used for the following applications:

1. Indicative Personal Exposure Monitoring: monitoring the air quality that a single individual is exposed to while doing daily activities
2. Indicating Monitoring Data: placing sensors within an existing state/local regulatory monitoring area to fill in coverage
3. Identification of hot spots
4. Education: using sensors in educational settings for science, technology, engineering, and math lessons
5. Information/Awareness: using sensors for informal air quality assessment

While using sensor-based instruments for above applications, it should be kept in mind that values given by sensor based instruments are indicative. The performance of these instruments is subject to periodic calibration and people from non-scientific communities may not be aware or inclined to do the periodic calibration. In such cases, the performance of these instruments may deteriorate, causing false alarm and panic.

# Interferences

**Humidity**

Humidity affects the sensor in many ways. The size of hygroscopic particles is dependent on RH, as the particle refractive index and size both are functions of RH. Therefore, it is necessary to determine the threshold RH above which sensor overestimates the concentration. Few sensors also consist of internal heaters that control the threshold RH to prevent overestimation of concentration. Overall, all sensors require the calibration both in laboratory and field condition and correction factor to correct the generated data.

**Temperature**

The individual effect of temperature is negligible on the sensor data accuracy, however, the combined effect of ambient temperature and humidity affect the particle morphology. Under low ambient temperature and high RH conditions, the air flow path inside the sensor may form water droplets because of condensation of water vapours, which may deteriorate the data quality and also sensor life. The effects can be observed where temperature diurnal variation is large. To evaluate the condition, the ambient dew point temperature monitoring is required.

**Air Flow**

The sensor data quality is dependent on constant air flow supply inside the detection system. Variation in air flow can affect the aerosol path exposed at a light beam, hence its scattering and consequently output data. In addition to this some sensors are designed to utilize incoming air to cool the internal circuits also. Therefore, the flow quality needs to be checked with sensitive flow meters (e.g. hotwire anemometer, mass flow meter, etc.).

**Dust Loading**

The maximum detection limit should be known for the sensor. Deposition of particles over the photodetector of the sensor may decrease detector measurement efficiency.

**Other interferences**

Wind direction and speed can cause variability in data accuracy, if sensor inlet is exposed to the environment in a different direction. This cause poor sampling of bigger fraction of particles (>2.5 𝜇m).

# Operation Requirements

## **Method of Measurement**

The instrument shall be including laser scattering or any equivalent aerosol measurement techniques as the technology for measurement of particulate matter concentration. The concentration of particulate matter is reported in µg/m3.

## **Sampling**

Samples are collected at flow rates from 0.1 l/min or more in continuous mode.

## **Battery Life**

The system shall have 24-hour backup (with no grid or solar power). System shall be able to run in 220 V, 50 Hz power line or DC supply.

## **Instrument Housing**

The instrument shall be placed in a weather-proof, dust-proof and water-proof enclosure. Dust-proof capability shall be as per IP55 or IP65.

## **Data Storage and Communication**

The instrument shall be able to store data for 48 hours in case of power failure or connectivity loss. It shall have in-built data logger and ethernet/GPRS/Wi-Fi module/any relevant new technology for communication of data to servers.

## **Environmental Operating Conditions**

The instrument can be operated at temperatures ranging from 0 – 50 ⁰C and relative humidity range 0 – 95%.

## **Instrument Cleaning and Storage**

The instruments shall be cleaned and stored as per manufacturer's instructions.

## **Online RH and Temperature Monitoring**

Monitoring of RH and temperature by the system is mandatory and provision for RH correction shall be made by the manufacturer.

## **Reporting Interval**

Minimum reporting interval of 1 minute or configurable.

# Calibration and Performance Evaluation Procedure

Different aspects of PM sensor must be checked to determine overall quality of PM sensor. The testing method of sensor shall be performed in both laboratory and field condition. This testing parameters are:

1. **Field comparison**

Evaluation of sensor at ambient outdoor site provides information on PM sensor performance that is relevant to real world condition and allow user to predict how the sensor might perform in similar condition.

1. **Relative Humidity and Temperature effect**

Compare a test PM concentration with elevated RH and temperature to see effect on PM sensor.

1. **Accuracy at low, mid and high concentration**

Determine PM sensor performance when exposed to test conditions with low, mid and high concentrations.

1. **Drift**

Compare the PM sensor response to test PM concentration before and after the sensors are operated for specified time period of 15, 30, 45 and 60 days in air.

To test the above parameters, the testing approach and outline of method is given below:

Field deployment for Comparison

**Laboratory chamber testing**

* Accuracy at different PM levels
* Drift testing (Day 15, 45 and 60)

**Laboratory chamber testing**

* Relative Humidity and Temperature effect
* Accuracy at different PM levels
* Drift testing (Day 1)

Field deployment for Comparison

**Field comparison**

**Statistical calculation can be referred to Annex-B.**

**Materials and Equipment**

* Reference PM2.5 and PM10 sampler (gravimetric method).
* PTFE filters (47 mm diameter, 2 µm pore size).
* Three (3) or more PM air sensors having the same make, model, and firmware version
* Calibrated PM2.5 and PM10 continuous monitor (BAM monitor)
* Calibrated RH monitor
* Calibrated T monitor
* Gravimetric measurement weighing facility

**Method**

1. Co-locate the reference PM2.5 and PM10 sampler and BAM monitors and three sensors of the same model at ambient location.

Co-location guidelines

* Mount sensors within 2-3 meters horizontal of the reference monitor
* Mount sensors in a location where they are exposed to unrestricted air flow
* Ensure the air sampling inlet for the sensors are within a height of ± 1 meter vertically of the air sampling inlet of the reference monitor
* Mount identical sensors ~1 meter apart from each other
* If necessary, install sensors within a weather-protective shelter/enclosure that maintains ample air flow around the sensor
1. Monitor temperature, humidity and pressure of ambient environment
2. Start the sampling simultaneously (at the same time) and note down the start time and make sure the time shown by reference instrument and PM sensor is common otherwise calibrate the timing with common standard clock (e.g., NPL India standard).
3. Stop the sampling at 24 hours of reference PM2.5 and PM10 sampler (Manual method)
4. Record the daily start and stop time
5. Repeat the step 1-4 for a minimum of 60 samples.
6. Record the data generated from PM sensor, reference monitors (manual and continuous).

**Laboratory chamber testing**

This test measures the Temperature and humidity effect over the sensor, drift and accuracy of sensor. **Statistical calculation can be referred to Annex-C.**

**Materials and Equipment**

1. Environmental chamber (T: 15 - 40 °C, RH: 35-95%, PM levels :10 -500 µg/m3).Testing should be performed at least three different conditions

**Specification/selection criteria**

* Ability to control, maintain, and monitor T, RH, and PM concentrations.
* recommended ranges based on testing conditions outlined in this report: T :15 to 40°C; RH: 35 to 95%; PM of desired concentration of 10-500 µg/m3.
* Ability to maintain the particle size distribution, composition, and concentration.
* Ability to maintain atmospheric pressure by balancing the incoming flow with the sampling and vent flow.
* Allows for air to be well-mixed.
* Capable of accommodating three (3) or more air sensors.
* Sampling ports should not be obstructed and allow for sufficient sampling flow.
* The particle generation system should be positioned above the exposure chamber and connected with as few bends as possible to prevent particle loss and build-up before particles enter the chamber.
* The PM FEM monitor should be mounted directly below the sampling chamber to reduce particle loss in the sampling line due to bends.(drawing from NPL to be provide)
1. Calibrated Temperature, humidity and pressure probe and data logger
2. Certified reference material: Ambient PM dust
3. Reference particle monitor (continuous)
4. Aerosol generator
5. Neutraliser
6. Mixing fan
7. Aerosol sampling probes

**Method**

1. Place three sensors of the same model inside the environmental chamber.
2. Place the aerosol sampling probes inside the chamber
3. Connect the outlet of probes to the reference monitor placed outside the environmental chamber for reference sampling.
4. Seal the chamber to prevent particle intrusion from outside.
5. Monitor temperature, humidity and pressure of the chamber.
6. Set the temperature and humidity of the environmental chamber (mentioned in Table A and B) and wait till it get stabilized. Ensure the pressure inside is equivalent to ambient pressure.
7. Monitor and log the zero-particle concentration with a reference monitor and note the minimum detection limit (zero) of the sensor.
8. Start an aerosol generator coupled with a neutralizer placed outside the chamber and

mix the particles in a chamber by mixing fans.

1. Maintain the chamber dust particle concentration as desired test condition mentioned in Table A, B and C.
2. Monitor and log the particle concentration with reference monitor and sensor.
3. This will give data of linearity between reference monitor and sensor both at different temperature,humidity and PM concentration.

(Counter to be added by NPL)

**Table A: RH test condition**

|  |  |
| --- | --- |
| **Parameter** | **Reference setpoint** |
| **PM concentration (2.5 or 10)** | 60±5% µg/m3 |
| **T** |  25°C ± 1°C |
| **RH** | 85% ± 5% |

 **Table B: Temperature test condition**

|  |  |
| --- | --- |
| **Parameter** | **Reference setpoint** |
| **PM concentration (2.5 or 10)** |  60±5% µg/m3 |
| **T** |  40°C ± 1°C |
| **RH** |  40% ± 5% |

# Table C: Accuracy and drift test condition

|  |  |
| --- | --- |
| **Parameter** | **Reference setpoint** |
| **PM concentration (2.5 or 10)** | Very low:10±10% µg/m3 |
| Low:35±10% µg/m3 |
| Mid:100±5% µg/m3 |
| High:200±2% µg/m3 |
| Higher:350±2 µg/m3 |
| **T** |  25°C ± 1°C |
| **RH** |  40% ± 5% |

# Intermediate Checks

Intermediate check of instrument shall be done, quarterly or more, against reference standard dust. Maximum acceptable error is ±10%.Three equipment of each batch will be taken for the intermediate calibration check at NMI

# Collocation Check

Collocation check of instrument shall be carried out at least once a year against BAM or equivalent reference method. Measurement duration shall be minimum 24 hour. Acceptable linear regression coefficient is minimum 0.75.

# Performance Requirements

The sensor-based instruments shall satisfy the performance requirements prescribed in Table 1.For definitions check Annex-A.

**Table 1 Performance Requirements of Sensor Based Instruments**

|  |  |  |  |
| --- | --- | --- | --- |
| **SL. NO.** | **PERFORMANCE CHARACTERISTICS** | **LABORATORY** | **FIELD** |
|  | Range of measurement , µg/m3 | PM2.5: 10-500 PM10: 10-500  | PM2.5: 10-500 PM10: 10-500 |
|  | Minimum Detection Limit, µg/m3 | 10  | 10  |
|  | Minimum detectable size, μm  | 0.3  | 0.3  |
|  | Precision on reported value (*Min*), % | ± 15 | ± 15 |
|  | Accuracy, %  | 25 | 25 |
|  | Response time, *s* | ≤ 30  | ≤ 30  |
|  | Completeness, % | > 90 | > 90 |
|  | Measurement Uncertainty, %  | PM2.5: 30% at 300 µg/m3PM10: 30% at 500 µg/m3 | PM2.5: 30% at 300 µg/m3PM10: 30% at 500 µg/m3 |
|  | Inter-model variability (*Max*), % | ± 10 | ± 10 |

Performance test methods mentioned above (Cl 7)

**Sensor performance evaluation and metrics**

Annex-A

The performance metrics based on testing above parameters is summarised in table:

|  |  |  |
| --- | --- | --- |
| Test type | Metric | Description |
| Field comparison | Precision | Variation around the mean of a set of measurements reported concurrently by three or more sensors of the same type collocated under the same sampling conditions. Precision is measured here using the standard deviation (SD) and coefficient of variation (CV). |
|  | Bias | The systematic (non-random) or persistent disagreement between the concentrations reported by the sensor and reference instruments. Bias is determined here using the linear regression slope and intercept. |
|  | Linearity | A measure of the extent to which the measurements reported by a sensor are able to explain the concentrations reported by the reference instrument. Linearity is determined here using the coefficient of determination (R2). |
|  | Error | A measure of the disagreement between the pollutant concentrations reported by the sensor and the reference instrument. Error is measured here using the root mean square error (RMSE) and normalized root mean square error (NRMSE). |
| Laboratory Chamber testing | Precision | Variation around the mean of a set of measurements reported concurrently by three or more sensors of the same type collocated under the same sampling conditions. Precision is measured here using the standard deviation (SD) and coefficient of variation (CV). |
|  | Bias | The systematic (non-random) or persistent disagreement between the concentrations reported by the sensor and reference instruments. Bias is determined here using the linear regression slope and intercept. |
|  | Linearity | A measure of the extent to which the measurements reported by a sensor are able to explain the concentrations reported by the reference instrument. Linearity is determined here using the coefficient of determination (R2). |
|  | Error | A measure of the disagreement between the pollutant concentrations reported by the sensor and the reference instrument. Error is measured here using the root mean square error (RMSE) and normalized root mean square error (NRMSE). |
|  | Effect of Relative Humidity (RH) | A positive or negative measurement response caused by variations in RH and not by changes in the concentration of the target pollutant. |
|  | Effect of Temperature (T) | A positive or negative measurement response caused by variations in ambient T and not by changes in the concentration of the target pollutant |
|  | Drift | A change in the response or concentration reported by a sensor when challenged by the same pollutant concentration over a period of time during which the sensor is operated continuously |
|  | Accuracy at HighConcentrations | A measure of the agreement between the pollutant concentrations reported by the sensor and the reference instrument during high concentration levels |

***Annex-B***

**Field comparison calculations**

**Daily Averages**

Performance metrics are calculated from daily (24-hour) averaged data. Any
FRM/FEM, sensor, RH, and/or T data collected as sub-daily time intervals will first need to be
averaged up to daily averages. In calculating these averages, a 75% data completeness
requirement for each 24-hour interval should be imposed. For example, a PM sensor recording concentration measurements every hour would require a minimum of 18 valid measurements in order to calculate a valid 24-hour averaged concentration [i.e., (18/24) \* 100% = 75%]

$$x\_{kdj}=\frac{1}{n}\sum\_{i=1}^{n}c\_{ij}$$

Where:

$$x\_{kdj}=24-hour averaged measurement k for day d and instrument j \left({μg}/{m^{3}}, °C, \% RH\right)$$

$n=$number of instrument measurements per 24−hour period

$$c\_{ij}= measurement from instrument j for time i of the 24-hour period ({μg}/{m^{3}}, °C, \% RH) $$

**Deployment Averages**

The average concentrations and meteorological parameters for the entire 30-day deployment should be reported. Deployment averaged measurements should be calculated from valid 24-hour averaged data for each field test.

$$\overline{x\_{k}}=\frac{1}{M}\sum\_{j=1}^{M}\left[\frac{1}{N}\sum\_{d=1}^{N}x\_{dj}\right]$$

Where:

$\overline{x\_{k}}$=deployment averaged measurement k for a field test (${μg}/{m^{3}}$, °C, % RH)

$M=$number of identical instruments operated simultaneously during a field test

$N=$number of 24-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test

$x\_{dj}=$ valid 24-hour averaged measurement for day d and instrument j (${μg}/{m^{3}}$, °C, % RH)

**Precision**

Precision between identical sensors should be characterized by two metrics: standard deviation (SD) between measurements and coefficient of variation (CV). These metrics should be calculated for the base testing field deployments using data during which all identical sensors are operating and returning valid 24-hour averaged measurements

$$SD=\sqrt{\frac{1}{\left(N×M\right)-1}\sum\_{j=1}^{M}\left[\sum\_{d=1}^{N}\left(x\_{dj}-\overline{x}\_{d}\right)^{2}\right]}$$

where:

$$SD= standard deviation of 24 hour averaged sensor PM concentration $$

$measurements ({μg}/{m^{3}}) $

$M=$number of identical sensors operated simultaneously during a field test $ $

$N= $number of 24-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test

$x\_{dj}= $24−hour averaged sensor PM concentration for day d and sensor j (${μg}/{m^{3}}$)

$\overline{x}\_{d}= $24−hour averaged sensor PM concentration for day d (${μg}/{m^{3}}$)

$$CV=\frac{SD}{\overline{x}} ×100$$

where:

$CV=$coefficient of variation (%)

$$SD= standard deviation of 24 hour averaged sensor concentration $$

$measurements ({μg}/{m^{3}}) $

$\overbar{x}= $deployment averaged sensor PM2.5 concentration for a field test (${μg}/{m^{3}}$)

**Bias and Linearity**

A simple linear regression model can demonstrate the relationship between paired 24-hour averaged sensor and FRM/FEM PM measurements. Using a simple linear regression model (y = mx + b) with the sensor PM measurements as the dependent variable (y) and the FRM/FEM PM measurements as the independent variable (x), calculate the slope (m), intercept (b), and the coefficient of determination (R2).
A simple linear regression model for each identical sensor (with corresponding graphical figures) are recommended. Comparison of the figures and these metrics across identical sensors can be helpful in further visualizing sensor precision. Sensors with very similar regression models and higher R2 values are typically more precise than those with different regression models and lower R2 values.

**Error**

The root mean square error (RMSE) is one metric that can be used to help understand the error associated with sensor PM2.5 concentration measurements. The interpretation of this value is slightly more straightforward because it is calculated in concentration units. Using data during which all sensors are reporting valid 24-hour averaged measurements, the sensor and FRM/FEM PM measurement calculations are compared. This equation assumes only one FRM/FEM instrument will be running. If multiple FRM/FEM instruments are running, separate testing reports can be generated for each.

$$RMSE=\sqrt{\frac{1}{\left(N×M\right)}\sum\_{j=1}^{M}\left[\sum\_{d=1}^{N}\left(x\_{dj}-R\_{d}\right)^{2}\right]}$$

where:

$$RMSE= root mean square error ({μg}/{m^{3}}) $$

$M=$number of identical sensors operated simultaneously during a field test $ $

$N= $number of 24-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test

$x\_{dj}= $valid 24−hour averaged sensor PM concentration for day d and instrument j (${μg}/{m^{3}}$)

$R\_{d}=valid $24−hour averaged FRM/FEM PM concentration for day d (${μg}/{m^{3}}$)

**Effect of Meteorology**

Here are several ways to investigate the potential influence using data from the field tests but, no single plot has proven useful in visualizing these effects for all sensor types. Here, several graphical ways to plot the data are suggested to try to understand the effect of meteorology. Additional ways may exist. Testers are encouraged to illustrate the effects of meteorology using one or more graphs that show the most profound or consistent effects for each field deployment.

Potential Scatter Plots

Sensor measurements should be plotted on the y-axis (dependent variable) with the meteorological parameter measurements (as measured by the T and RH monitors, rather than on-board T and RH sensor measurements) on the x-axis (independent variable). Normalized concentration (in other words, the ratio of sensor to FRM/FEM concentration), concentration difference, absolute concentration difference, and DP calculations are discussed in the list below. It is recommended that testers choose plots from this list.

• 24-hour averaged normalized sensor PM concentration vs. 24-hour averaged DP
• 24-hour averaged normalized sensor PM concentration vs. 24-hour averaged RH
• 24-hour averaged normalized sensor PM concentration vs. 24-hour averaged T
• 24-hour averaged concentration difference between the sensor and FRM/FEM PM
concentration vs. 24-hour averaged DP
• 24-hour averaged concentration difference between the sensor and FRM/FEM PM
concentration vs. 24-hour averaged RH
• 24-hour averaged concentration difference between the sensor and FRM/FEM PM
concentration vs. 24-hour averaged T
• 24-hour averaged absolute concentration difference between the sensor and FRM/FEM PM
concentration vs. 24-hour averaged DP
• 24-hour averaged absolute concentration difference between the sensor and FRM/FEM PM
concentration vs. 24-hour averaged RH
• 24-hour averaged absolute concentration difference between the sensor and FRM/FEM PM
concentration vs. 24-hour averaged T

Annex-C

**Laboratory chamber testing calculations**

**Test Averages**

Test averaged measurements should be calculated from valid averaged data collected during the steady state period for each test.

$$\overline{x\_{k}}=\frac{1}{M}\sum\_{j=1}^{M}\left[\frac{1}{N}\sum\_{h=1}^{N}x\_{ktj}\right]$$

Where:

$\overline{x\_{k}}$=deployment averaged measurement k for a field test (${μg}/{m^{3}}$, °C, % RH)

$M=$number of identical instruments operated simultaneously during a field test

$N=$number of 24-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test

$x\_{ktj}=$ valid 24-hour averaged measurement for day d and instrument j (${μg}/{m^{3}}$, °C, % RH)

**Precision**

Precision between identical sensors can be characterized by two metrics: standard deviation (SD)
between measurements and coefficient of variation (CV). This metric should be calculated from valid averaged data collected during the mid-concentration test condition during the post-aging (Day 15,45,60) drift test.

$$SD=\sqrt{\frac{1}{\left(N×M\right)-1}\sum\_{j=1}^{M}\left[\sum\_{t=1}^{N}\left(x\_{tj}-\overline{x}\_{t}\right)^{2}\right]}$$

where:

$$SD= standard deviation of 24 hour averaged sensor PM concentration $$

$measurements ({μg}/{m^{3}}) $

$M=$ number of identical sensors operated simultaneously during the chamber test

$N= $number of valid time intervals during which all identical instruments are operating and returning valid averages over the duration of the chamber test

$x\_{tj}= $averaged sensor PM concentration for time interval t and sensor j (${μg}/{m^{3}}$)

$\overline{x}\_{t}= $test averaged sensor PM concentration for day t (${μg}/{m^{3}}$)

$$CV=\frac{SD}{\overline{x}} ×100$$

where:

$CV=$coefficient of variation (%)

$$SD= standard deviation of 24 hour averaged sensor PM concentration $$

$measurements ({μg}/{m^{3}}) $

$\overbar{x}= $deployment averaged sensor PM2.5 concentration for a field test (${μg}/{m^{3}}$)

**Bias and Linearity**

A simple linear regression model can demonstrate the relationship between paired averaged sensor and FEM PM measurements. During enhanced testing, pooling the data collected during the steady state period of the low and mid concentration test conditions during the post-aging (Day 60) drift test and the high and higher concentration tests will reflect data collected under similar T and RH conditions. Using a simple linear regression model (y = mx + b) with the sensor PM2.5 measurements as the dependent variable (y) and the FEM PM2.5 measurements as the independent variable (x), calculate the slope (m), intercept (b), and the coefficient of determination (R2) for each test.

**Error**

The root mean square error (RMSE) is one metric that can be used to help understand the error associated with sensor PM concentration measurements. The interpretation of this value is slightly more straightforward because it is calculated in concentration units. This metric should be calculated from valid averaged data collected during the mid-concentration test condition during the post-aging (Day 60) drift test. Using data during which all sensors are reporting valid time averaged measurements, the sensor and FEM PM measurement calculations are compared. This equation assumes only one FEM instrument will be running. If multiple FEM instruments are running, separate testing reports can be generated for each.

$$RMSE=\sqrt{\frac{1}{\left(N×M\right)}\sum\_{j=1}^{M}\left[\sum\_{t=1}^{N}\left(x\_{tj}-R\_{t}\right)^{2}\right]}$$

where:

$$RMSE= root mean square error ({μg}/{m^{3}}) $$

$M=$number of identical sensors operated simultaneously during a field test $ $

$N= $number of 24-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test.

$x\_{tj}= $averaged sensor PM concentration for time interval t and instrument j (${μg}/{m^{3}}$)

$R\_{t}=$averaged FRM/FEM PM concentration for time t (${μg}/{m^{3}}$)

**Effect of Relative Humidity (RH)**

The RH tests on sensor measurements involve two steps: 1) collecting data during steady state at a prescribed PM concentration at 40% RH, and 2) collecting data during steady state at the same prescribed PM concentration at 85% RH. The effect of RH is the difference between these two measurements.

$$\overbar{x\_{RH}}=\overbar{x\_{(RH=85\%)}}- \overbar{x\_{(RH=40\%)}}$$

Where:

$\overbar{x\_{RH}}=$ test averaged influence of RH on sensor measurements (µg/m3)

$\overbar{x\_{(RH=85\%)}}$= test averaged sensor PM concentration for the portion of the chamber test when the RH is 85% (µg/m3)

$\overbar{x\_{(RH=40\%)}}=$test averaged sensor PM concentration for the portion of the chamber test when the RH is 40% (µg/m3)

**Effect of Temperature (T)**

The T tests on sensor measurements involve two steps: 1) collecting data during steady state at a prescribed PM concentration at 25°C, and 2) collecting data during steady state at the same prescribed PM concentration at 40°C. The effect of T is the difference between these two measurements.

$$\overbar{x\_{T}}=\overbar{x\_{(T=40)}}- \overbar{x\_{(T=20)}}$$

Where:

$\overbar{x\_{T}}=$ test averaged influence of T on sensor measurements (${μg}/{m^{3}}$)

$\overbar{x\_{(T=40)}}$= test averaged sensor PM concentration for the portion of the chamber test when the RH is 40 °C (${μg}/{m^{3}}$).

$\overbar{x\_{(T=20)}}=$test averaged sensor PM concentration for the portion of the chamber test when the T is 20 °C (${μg}/{m^{3}}$).

**Drift**

The drift tests involve measuring the drift at two PM concentrations: 1) at a low concentration of 10 µg/m3, and 2) at a mid-concentration of 100 µg/m3 which is relevant for health messaging. For each PM concentration, the drift measurement includes two separate chamber tests. The first will be conducted to determine the steady state concentration for the prescribed PM concentration. The sensors will then be operated continuously and tested again at least 60 days later to
see if the measurement has drifted. The amount of drift will be quantified for both PM concentrations by the difference in the measurement over the 60-day period.

$$\overbar{x\_{C\_{drift}}}=\overbar{x\_{C\_{(day=60)}}}- \overbar{x\_{C\_{(day=1)}}}$$

Where:

$\overbar{x\_{C\_{drift}}}= $test averaged sensor drift at PM concentration C over the course of 60 days (${μg}/{m^{3}}$)

$\overbar{x\_{C\_{(day=60)}}}= $test averaged sensor PM concentration at PM concentration C after 60 days of
operation following the start of the drift test (${μg}/{m^{3}}$)

$\overbar{x\_{C\_{(day=1)}}}= $test averaged sensor PM concentration at PM concentration C at the beginning of the drift test (${μg}/{m^{3}}$)

**Accuracy at High Concentrations**

The accuracy at high concentrations test involves testing the sensor response at a high PM concentration which is relevant for health messaging and a higher PM concentration which is relevant for PM events such as wildfires. The accuracy of the sensor measurement will be determined by the difference between the sensor and FEM measurements.

$$\overbar{x\_{∆}}=\overbar{x\_{sensor}}- \overbar{x\_{ref}}$$

Where:

$\overbar{x\_{∆}}=$ test averaged difference between the sensor and FEM PM concentrations (${μg}/{m^{3}}$)

$\overbar{x\_{sensor}}$= test averaged sensor PM concentration (${μg}/{m^{3}}$)

$\overbar{x\_{ref}}= $test averaged FEM PM concentration (${μg}/{m^{3}}$)