



Designation: D8406 – 22

Standard Practice for Performance Evaluation of Ambient Outdoor Air Quality Sensors and Sensor-based Instruments for Portable and Fixed-point Measurement¹

This standard is issued under the fixed designation D8406; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice establishes standardized tests for the performance evaluation of sensor-based continuous instruments for ambient outdoor air quality measurements. It describes both laboratory and field tests that provide information on candidate sensor repeatability, sensitivity, linearity, cross-interferences, drift, and comparability against reference instruments.

1.2 This practice does not apply to sensors or instruments that remotely measure atmospheric pollutants using open path, lidar, or imaging technology.

1.3 The evaluation procedures contained in this practice are for sensors that alone or in combination measure outdoor criteria pollutants in ambient air: particulate matter (PM_{2.5} and PM₁₀), sulfur dioxide (SO₂), ozone (O₃), carbon monoxide (CO), or nitrogen dioxide (NO₂) at concentrations that are relevant to public health.

1.4 Testing is to be performed by a competent entity able to demonstrate that it operates in conformity with internationally accepted test laboratory quality standards such as ISO/IEC 17025.

1.5 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

¹ This practice is under the jurisdiction of ASTM Committee D22 on Air Quality and is the direct responsibility of Subcommittee D22.03 on Ambient Atmospheres and Source Emissions.

Current edition approved Sept. 1, 2022. Published October 2022. DOI: 10.1520/D8406-22.

2. Referenced Documents

2.1 ASTM Standards:²

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

D1914 Practice for Conversion Units and Factors Relating to Sampling and Analysis of Atmospheres

D3162 Test Method for Carbon Monoxide in the Atmosphere (Continuous Measurement by Nondispersive Infrared Spectrometry)

D3249 Practice for General Ambient Air Analyzer Procedures

D3824 Test Methods for Continuous Measurement of Oxides of Nitrogen in the Ambient or Workplace Atmosphere by Chemiluminescence

D5011 Practices for Calibration of Ozone Monitors Using Transfer Standards

D5110 Practice for Calibration of Ozone Monitors and Certification of Ozone Transfer Standards Using Ultraviolet Photometry

D6332 Guide for Testing Systems for Measuring Dynamic Responses of Carbon Monoxide Detectors to Gases and Vapors

D8405 Test Method for Evaluating PM_{2.5} Sensors or Sensor Systems Used in Indoor Air Applications

E178 Practice for Dealing With Outlying Observations

E456 Terminology Relating to Quality and Statistics

E3080 Practice for Regression Analysis with a Single Predictor Variable

2.2 Other References:

29 CFR 1910.101 Compressed gases (general requirements)³

40 CFR Part 58 Ambient Air Quality Surveillance³

EN 14626:2012 Ambient air – Standard method for the measurement of the concentration of carbon monoxide by

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

³ Available from U.S. Government Publishing Office (GPO), 732 N. Capitol St., NW, Washington, DC 20401, <http://www.gpo.gov>.

- non-dispersive infrared spectroscopy⁴
EN 14625:2012 Ambient air – Standard method for the measurement of the concentration of ozone by ultraviolet photometry⁴
Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe⁴
ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories⁵
ISO 6145-7:2018 Gas analysis – Preparation of calibration gas mixtures using dynamic methods Part 7: Thermal mass-flow controllers⁵

3. Terminology

3.1 Definitions:

3.1.1 For definitions of terms used in this practice other than those following, refer to Terminologies **D1356** and **E456**.

3.1.2 *air quality sensor, n*—a physical device that uses one or more sensors to measure and report the concentration of one or more analytes (pollutants) in outdoor air.

3.1.3 *analyte, n*—the substance (air pollutant) measured by the air quality sensor or analyzer.

3.1.4 *full scale, n*—the designated maximum concentration for performance testing determined by either the measurement range of the sensor or the reference analyzer (whichever is lower).

3.1.5 *instrument, n*—see *air quality sensor*.

3.1.6 *interferent, n*—a substance other than the compound of interest that causes a bias in the sensor output.

3.1.7 *reading, n*—the analytical result obtained from a digital display or indicated on a scale or dial affixed to or recording output from a sensor or instrument.

4. Summary of Practice

4.1 This is a practice for evaluating ambient air quality sensor performance. This document contains definitions and terms, sampling information, calibration techniques, methods for validating results, and general comments related to ambient air sensors and sensor-based instruments. This practice is applicable to sensors and sensor-based instruments that sample ambient air through diffusion or passive sampling as well as through active sampling using a pump or fan. This practice comprises laboratory and field tests to evaluate performance of gas sensors and particulate matter sensors.

5. Significance and Use

5.1 This practice establishes standardized tests for the performance evaluation of sensor-based continuous instruments for ambient air quality measurements. Public and private air monitoring interests have manifested themselves as a driving force for the deployment of air quality sensors and instruments

to quantify air pollutant concentrations in communities, around schools, around industrial facilities, and elsewhere. Users of air quality sensors require information on the performance and limitations of these devices so that informed decisions regarding their suitability for various purposes can be determined. This practice describes both laboratory and field tests that provide information on candidate instrument repeatability, sensitivity, linearity, cross-interferences, drift and comparability with more costly instruments typically used by entities such as government agencies. The air quality sensors are first evaluated in a laboratory chamber by comparing their response to a reference instrument and challenging the gas sensors with interferences. The sensors are then deployed outdoors for field testing at two sites with different climates against reference air quality instruments. This practice is intended to be referenced in standards and codes that establish minimum performance quality for sensor-based ambient outdoor air monitoring.

5.2 This practice is intended for air quality sensors that measure one or more of the criteria pollutants in ambient air (ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide, PM₁₀ and PM_{2.5}) that can be operated in outdoor environments and can log a concentration reading. It is not intended for devices or transducers that require additional enclosures for deployment outdoors or post-processing to convert their output signal into a pollutant concentration reading.

5.3 It is anticipated that the main users of this practice will be manufacturers, developers, and distributors of outdoor air quality sensors, air quality agencies, and environmental consultants.

6. Apparatus

6.1 *Gas dilution and delivery system* for the continuous generation of test mixtures from gas standards and zero-air operated according to ISO 6145-7.

6.2 *Ozone analyzer* that is on the USEPA List of Designated Reference and Equivalent Methods for ozone or conforms to EN14625 or is on the MCERTS list of Certified Products: Continuous Ambient Air Monitoring System⁶ or has been approved by a national standards body for ambient monitoring and has been calibrated according to Practices **D5011**.

6.3 *Sulfur dioxide analyzer* that is on the USEPA List of Designated Reference and Equivalent Methods for sulfur dioxide or conforms to EN14212 or is on the MCERTS list of Certified Products: Continuous Ambient Air Monitoring System⁶ or has been approved by a national standards body for ambient monitoring.

6.4 *Nitrogen dioxide analyzer* that is on the USEPA List of Designated Reference and Equivalent Methods for nitrogen dioxide or conforms to EN14211 or is on the MCERTS list of Certified Products: Continuous Ambient Air Monitoring System⁶ or conforms to Test Methods **D3824** or has been approved by a national standards body for ambient monitoring.

⁴ Available from European Committee for Standardization (CEN), Avenue Marnix 17, B-1000, Brussels, Belgium, <http://www.cen.eu>.

⁵ Available from International Organization for Standardization (ISO), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, <https://www.iso.org>.

⁶ <https://www.csagroupuk.org/services/mcerts/mcerts-product-certification/mcerts-certified-products/mcerts-certified-products-continuous-air-monitoring-system/> (Accessed 26 May 2021).

6.5 *Carbon monoxide analyzer* that is on the USEPA List of Designated Reference and Equivalent Methods for carbon monoxide or conforms to EN14626 or is on the MCERTS list of Certified Products: Continuous Ambient Air Monitoring System⁶ or conforms to Test Method D3162 or has been approved by a national standards body for ambient monitoring.

6.6 *Continuous PM_{2.5} instrument* that is on the current USEPA List of Designated Reference and Equivalent Methods for PM_{2.5} or conforms to EN16450 or is on the MCERTS list of Certified Products: Continuous Ambient Air Monitoring System⁶ or has been approved by a national standards body for ambient monitoring.

6.7 *Continuous PM₁₀ instrument* that is on the current USEPA List of Designated Reference and Equivalent Methods for PM₁₀ or conforms to EN16450 or is on the MCERTS list of Certified Products: Continuous Ambient Air Monitoring System⁶ or has been approved by a national standards body for ambient monitoring.

6.8 *Aerosol generation system* able to produce monodisperse polystyrene latex spheres in the range 0.5 µm to 1.5 µm for the evaluation of PM_{2.5} sensors and in the range 4.0 µm to 8.0 µm for the evaluation of the PM₁₀ sensors.

6.9 *Exposure chamber* able to enclose the air quality sensors under test and expose them to test concentrations of pollutants. The chamber for testing gas sensors is constructed following the design principles described in Guide D6332 and be made of inert materials that will not react with the test gases. The chamber for PM_{2.5} and PM₁₀ sensor testing is constructed following the design principles described in Test Method D8405. The chamber has a means of bringing in outside ambient air to expose sensors to ambient conditions during periods between tests. A description of a suitable chamber design that meets the design principles for both gas and aerosol testing is given in the literature.⁷

6.10 *Zero-air source* for generating zero- air as described in Guide D6332 and which can generate zero-air with the specification defined in 7.3.

6.11 *Humidification module* for humidifying the zero-air and test gas as described in Guide D6332.

6.12 *Temperature measurement apparatus* able to measure from -10 °C to 50 °C with a maximum error of 0.5 °C calibrated against reference temperature standards according to the manufacturer’s instructions for recording test conditions.

6.13 *Humidity measurement apparatus* able to measure relative humidity from 10 % to 90 % RH with a maximum error of 3 % calibrated against reference humidity standards according to the manufacturer’s instructions for recording test conditions.

7. Reagents and Materials

7.1 *Ozone source* for generation of test mixtures of O₃ in air as described in Practices D5110 and D5011.

⁷ Papapostolou, Vasileios & Zhang, Hang & J. Feenstra, Brandon & Polidori, Andrea, “Development of an environmental chamber for evaluating the performance of low-cost air quality sensors under controlled conditions,” *Atmospheric Environment*, Vol 171, 2017, pp 82–90.

7.2 *Test Gas Mixtures (not ozone)*—These contain concentrations of the test gas in nitrogen or air. The gas mixtures are certified with ±2 % uncertainty of the stated value and are to be supplied in high- pressure cylinders.

7.3 *Zero-air*—Air that is substantively free of contaminants. The specification of the purity of the zero-air is given in Table 1. Zero-air is supplied at a temperature of 20 °C ± 2 °C and relative humidity of 30 % ± 5 %. Zero-air is used to dilute all calibration gases to produce the required test gas concentrations.

7.4 *Particle-free Air*—Dry air which has been filtered to contain PM₁₀ at a level of less than 1 µg/m³.

8. Hazards

8.1 Each sensor and manual is reviewed to ensure the sensor conforms to applicable electrical, optical, radio, and power safety requirements such as CE, FCC, IEC. If conformity is unclear, testing shall stop and the manufacturer contacted to provide documentation on safety in usage of the sensor and its components. Testing can resume once the test laboratory is satisfied that the sensor is safe to test.

8.2 Compressed gas standards shall be handled in accordance with 29 CFR 1910.101, in well-ventilated locations away from sparks and flames. Improper handling of compressed gas cylinders can result in explosion. Cylinders and permeation devices containing high purity CO and NO are flammable and harmful if inhaled. Cylinders containing mixtures of CO, SO₂, NO, and NO₂ in air or nitrogen may be harmful if inhaled. Rapid release of gas mixtures with nitrogen as the balance gas can result in asphyxiation. Compressed air supports combustion.

8.2.1 Gas cylinders must be fastened to a rigid structure and not exposed to direct sunlight or heat as per 29 CFR 1910.101.

8.2.2 Special safety precautions shall be taken when using or storing combustible or toxic gases to ensure that the system is safe and free from leaks. Review the Safety Data Sheets (SDS) for all materials and be sure to use proper safety precautions.

9. Procedure

9.1 Two identical air quality sensor units or instruments are needed for evaluation. All units are evaluated concurrently and the results for each unit are reported. If a fault or failure occurs with one or more of the units, the testing of the faulty units is stopped, the fault fixed or the units replaced, the previous test results invalidated, and all laboratory and field tests repeated.

9.2 Each test is performed for each analyte the sensor units measure. The laboratory tests are completed before the field

TABLE 1 Maximum Zero-air Pollutant Levels

Pollutant	Concentration
Ozone, Nitrogen dioxide, Sulfur dioxide, Hydrogen sulfide, Ammonia	Each pollutant ≤ 1 nmol/mol
Carbon monoxide	≤ 0.05 µmol/mol
Total hydrocarbons	≤ 0.5 µmol/mol

test. If the sensor has a pump-based sampling system which can be connected to a sampling line, the analyte test mixtures can be generated in the sampling line and supplied to the sensor provided the sample pressure is the same as ambient pressure. If the sensor uses diffusion or fan-based sampling or if the manufacturer requests it, then the sensor is exposed to analyte test mixtures inside the exposure chamber (6.9).

9.3 All test concentrations are measured using the reference analyzers described in Section 6. All reference analyzers shall be calibrated within one week of the start of the laboratory tests according to the manufacturer's instruction. All reference analyzers shall be zero and span adjusted at 70 % to 80 % of full scale (see 3.1.4) each day prior to the start of laboratory tests. The sensors shall also be zero and span adjusted at 70 % to 80 % of full scale each day, using the same reference standard, prior to the start of laboratory testing. If the sensors are not able to be zero and span adjusted, they should be tested without adjustment. Temperature and humidity of the test mixtures generated shall be $20\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ and $30\text{ \%} \pm 2\text{ \% RH}$ respectively, unless otherwise stated.

9.4 *Laboratory Evaluation of O₃, NO₂, SO₂, CO, Sensors and Sensor-based Instruments*—Ensure the test sensors are warmed up and operating according to the manufacturer instructions and are calibrated. All laboratory test readings must be recorded at one minute intervals or the minimum reporting frequency of the sensor if this is greater than one minute.

9.4.1 Lack of Fit:

9.4.1.1 Supply the sensor with analyte concentrations at 0 %, 95 %, 25 %, 75 %, and 50 % of full scale in that order. Once the correct concentration is reached by the gas delivery system according to the reference analyzer, wait for 30 min and then record the mean of the next 10 readings of the sensor and analyzer. Calculate the linear regression through the mean responses at each concentration according to Practice E3080. The residuals at each concentration are calculated according to:

$$r_c = Y_{a,c} - (A + Bc) \quad (1)$$

where:

- r_c = residual at concentration c ,
- $Y_{a,c}$ = mean of the 10 sensor readings at each concentration c ,
- A = intercept of the linear regression line,
- B = slope of the linear regression line, and
- c = mean concentration measured by the reference analyzer at test point.

9.4.1.2 Calculate the residual at zero concentration (r_z) and the relative residuals at each non-zero concentration ($r_{c,rel}$) according to:

$$r_{c,rel} = \frac{r_c}{c} \times 100 \quad (2)$$

9.4.1.3 The largest value of $r_{c,rel}$ is the maximum relative residual (r_{max}).

9.4.1.4 Calculate the laboratory coefficient of determination (r^2) according to Practice E3080.

9.4.2 Repeatability at Zero:

9.4.2.1 Provide zero-air to the instrument as confirmed by the reference analyzer, wait for 30 min and then record the next 20 independent results ($X_{z,i}$). The repeatability at zero is defined as the standard deviation (S_0) calculated according to:

$$S_0 = \sqrt{\frac{\sum_{i=1}^n (X_{z,i} - \bar{X})^2}{n - 1}} \quad (3)$$

where:

- S_0 = standard deviation at zero,
- n = number of measurements,
- $X_{z,i}$ = consecutive individual sensor results at zero, and
- \bar{X} = mean of individual sensor results at zero.

9.4.3 Repeatability at Span:

9.4.3.1 Supply the sensor under test with the test analyte at the concentration given in Table 2 as confirmed by the reference analyzer, wait for 30 min and then record the next 20 independent results ($X_{s,i}$).

9.4.3.2 The repeatability at span is defined as the standard deviation (S_s) calculated according to:

$$S_s = \sqrt{\frac{\sum_{i=1}^n (X_{s,i} - \bar{X})^2}{n - 1}} \quad (4)$$

where:

- S_s = standard deviation at span,
- n = number of measurements,
- $X_{s,i}$ = consecutive individual sensor results at span, and
- \bar{X} = mean of individual sensor results at span.

9.4.4 Limit of Detection:

9.4.4.1 The limit of detection (LOD) for the sensor measurement of the analyte is given by:

$$\text{LOD} = 3S_0 \quad (5)$$

9.4.5 Short-term Drift:

9.4.5.1 Supply zero-air and wait 30 min then record 20 independent readings and calculate the mean ($C_{z,1}$). Supply the analyte gas at the stated test concentration in Table 2, for 30 min then record 20 independent readings and calculate the mean ($C_{s,1}$). Keep the sensor running for 24 h sampling outdoor ambient air. After 24 h, supply zero-air and wait 30 min then record 20 independent readings and calculate the mean ($C_{z,2}$). Supply analyte gas at the same concentration as supplied at the start of the test for 30 min then record 20 independent readings and calculate the mean ($C_{s,2}$).

9.4.5.2 Calculate the short-term zero drift (D_z) (in nmol/mol for O₃, NO₂ and O₃ and in μmol/mol for CO) and the short-term span drift (D_s), expressed as a percentage of reading, as follows:

$$D_z = (C_{z,1} - C_{z,2}) \quad (6)$$

TABLE 2 Test Concentrations for Repeatability and Drift at Span

Analyte	Concentration
SO ₂	100 nmol/mol
O ₃	100 nmol/mol
CO	20 μmol/mol
NO ₂	100 nmol/mol

$$D_s = \frac{(C_{s,1} - C_{s,2} - D_z)}{C_{s,1}} \times 100 \% \quad (7)$$

9.4.6 Temperature Sensitivity:

9.4.6.1 The sensitivity of the sensors to temperature is determined by performing measurements at test temperatures of $T_1 = 5\text{ }^\circ\text{C}$ and then $T_2 = 30\text{ }^\circ\text{C}$ with a constant dewpoint of $2\text{ }^\circ\text{C} \pm 1\text{ }^\circ\text{C}$ to avoid condensation. Before starting, calibrate the sensor zero and span at the temperature and relative humidity conditions given in 9.3 using the span test concentrations given in Table 2. Determine the sensors response at the span points defined in Table 2, at each test temperature T_1 and T_2 , keeping the dewpoint constant at $2\text{ }^\circ\text{C} \pm 1\text{ }^\circ\text{C}$. When each test temperature is reached, allow the sensor to stabilize for 30 min and then record the mean of 10 readings of the test gas. The sensitivity to temperature is calculated as follows:

$$b_{temp} = \left| \frac{(C_{T2} - C_{T1})}{(T_2 - T_1)} \right| \quad (8)$$

where:

b_{temp} = the temperature response y in nmol/mol/ $^\circ\text{C}$ or $\mu\text{mol/mol}/^\circ\text{C}$,

C_{T1} = the mean concentration of the 10 sensor readings at temperature T_1 ,

C_{T2} = the mean concentration of the 10 sensor readings at temperature T_2 ,

T_1 = the lower temperature in $^\circ\text{C}$, and

T_2 = the higher temperature in $^\circ\text{C}$.

9.4.7 Cross-interferences:

9.4.7.1 The test sensor is challenged with each interferent one at a time as specified for the sensor in Table 3. The interference test is performed at zero and at the test concentrations in Table 2 for each interferent except for NO which is only performed at zero only for SO₂ and O₃ sensors. Before starting the test, calibrate the sensor at zero and at the pollutant test concentration in Table 2.

9.4.7.2 *Interference at Zero*—Supply the sensor with zero-air, wait for 30 min then record the mean of the next 10 readings as x_z . Next supply the interferent at the correct concentration as determined by the reference analyzer, wait 30 min and record the mean of the next 10 readings as $x_{int,z}$.

9.4.7.3 *Interference at Span*—Supply the sensor with the pollutant test concentration as determined by the reference analyzer, wait for 30 min then record the mean of the next 10 readings as x_c . Next supply the interferent and the pollutant test concentration from Table 2, wait 30 min, and record the mean of the next 10 readings as $x_{int,c}$.

9.4.7.4 Calculate for each sensor and interferent the quantities:

$$X_{int,z} = X_{int,z} - X_z \quad \text{the influence of the interferent at zero} \quad (9)$$

$$X_{int,c} = X_{int,c} - X_c \quad \text{the influence of the interferent at span} \quad (10)$$

9.5 *Laboratory Evaluation of PM_{2.5} and PM₁₀ Sensors and Sensor-based Instruments*—Ensure the test sensors are warmed up and are operating according to the manufacturer instructions before starting the tests. The test sensors are tested using the correct size of monodisperse aerosol as described in 6.8. All laboratory test readings must be recorded at one minute intervals or the minimum reporting frequency of the sensor if this is greater than one minute.

9.5.1 Lack of Fit:

9.5.1.1 Supply the sensor with five aerosol target concentrations in the following order $0\text{ }\mu\text{g}/\text{m}^3$, $200\text{ }\mu\text{g}/\text{m}^3$, $25\text{ }\mu\text{g}/\text{m}^3$, $100\text{ }\mu\text{g}/\text{m}^3$ and $50\text{ }\mu\text{g}/\text{m}^3$. The test concentration at each point should be stable at a value within 10 % of the target concentration. Confirm the test concentration is stable (relative standard deviation of less than 5 % using the reference analyzer), and then record the mean of the next 10 readings of the sensor and reference analyzer. Calculate the linear regression function through the mean response at each concentration according to Practice E3080. The residuals at each concentration are calculated according to:

$$r_c = Y_{a,c} - (A + Bc) \quad (11)$$

where:

r_c = residual at concentration c ,

$Y_{a,c}$ = mean of the 10 sensor readings at each concentration

c ,

A = intercept of the linear regression line,

B = slope of the linear regression line, and

c = mean concentration measured by analyzer at test point.

9.5.1.2 Calculate the residual at zero concentration (r_z) and the relative residuals at each non-zero concentration ($r_{c,rel}$) according to:

$$r_{c,rel} = \frac{r_c}{c} \times 100 \quad (12)$$

9.5.1.3 The largest value of $r_{c,rel}$ is the maximum relative residual (r_{max}).

9.5.1.4 Calculate the laboratory coefficient of determination (r^2) according to Practice E3080.

9.5.2 Repeatability at Zero:

TABLE 3 Interferent Test Concentrations for the Test Sensors in $\mu\text{mol}/\text{mol}$, unless otherwise stated

Sensor	Interferent						Total Number of Tests for Sensor ^C
	H ₂ O ^A	SO ₂	NO ₂	NO	O ₃	CO	
SO ₂	19 mmol/mol	—	0.1	0.1 ^B	0.1	—	5
O ₃	19 mmol/mol	0.1	0.1	0.1 ^B	—	5	7
CO	19 mmol/mol	—	—	0.5	0.1	—	4
NO ₂	19 mmol/mol	0.1	—	0.5	0.1	5	6

^A A H₂O concentration of 19 mmol/mol equals 80 % RH at 20 $^\circ\text{C}$ and 101.3 kPa.

^B The SO₂ and O₃ sensors are challenged with NO at zero but not at span, due to the chemical reactivity of (O₃ + NO) and (SO₂ + NO) gas mixtures.

^C The total number of tests includes a zero and span test for each interferent except where noted for NO.

9.5.2.1 Supply particle free air to the sensor for 30 min and then record the next 20 independent results. The repeatability at zero is defined as the standard deviation (S_0) calculated according to:

$$S_0 = \sqrt{\frac{\sum_{i=1}^n (X_{z,i} - \bar{X})^2}{n - 1}} \quad (13)$$

where:

- S_0 = standard deviation at zero,
- n = number of measurements,
- $X_{z,i}$ = consecutive individual sensor results at zero, and
- \bar{X} = mean of individual sensor results at zero.

9.5.3 Repeatability at Span:

9.5.3.1 Supply the aerosol at a stable test concentration of $100 \mu\text{g}/\text{m}^3 \pm 10 \mu\text{g}/\text{m}^3$ as determined by the reference dust analyzer. Confirm the test concentration is stable (relative standard deviation of less than 5 % using the reference analyzer), and then record the next 20 independent results.

9.5.3.2 The repeatability at span is defined as the standard deviation (S_s) calculated according to:

$$S_s = \sqrt{\frac{\sum_{i=1}^n (X_{s,i} - \bar{X})^2}{n - 1}} \quad (14)$$

where:

- S_s = standard deviation at the test concentration,
- n = number of measurements,
- $X_{s,i}$ = consecutive individual sensor results at the test concentration, and
- \bar{X} = mean of individual sensor results at the test concentration.

9.5.4 Limit of Detection:

9.5.4.1 The limit of detection (LOD) for the sensor measurement of the pollutant is given by:

$$\text{LOD} = 3S_0 \quad (15)$$

9.5.5 Short-term Drift:

9.5.5.1 Calibrate the sensor at zero and at a concentration of $200 \mu\text{g}/\text{m}^3$. Supply particle-free air and wait 30 min then record 20 independent readings and calculate the mean ($C_{z,1}$). Supply the monodisperse test aerosol at a stable concentration of $100 \mu\text{g}/\text{m}^3 \pm 10 \mu\text{g}/\text{m}^3$. Confirm the test concentration is stable (relative standard deviation of less than 5 % using the reference analyzer) and then record 20 independent readings and calculate the mean ($C_{s,1}$). Keep the sensor running for 24 hours sampling outdoor ambient air. After 24 hours, supply particle-free air and wait 30 min then record 20 independent readings and calculate the mean ($C_{z,2}$). Supply the test aerosol at the same concentration as supplied at the start of the test and when the concentration is confirmed stable as before, record 20 independent readings and calculate the mean ($C_{s,2}$).

9.5.5.2 Calculate the short-term zero drift (D_z) (in $\mu\text{g}/\text{m}^3$) and the short-term span drift (D_s), expressed as a percentage of reading, as follows:

$$D_z = |(C_{z,1} - C_{z,2})| \quad (16)$$

$$D_s = \frac{|(C_{s,1} - C_{s,2} - D_z)|}{C_{s,1}} \times 100 \% \quad (17)$$

9.6 Field Evaluation of Sensors and Sensor-based Instruments—Two sensors of the same type (model, hardware design, software version) are tested in each field evaluation. The field evaluation is undertaken at two test sites with different primary climate types according to the Köppen-Geiger climate classification scheme.^{8,9} See Table 4. No augmentation of pollutant concentrations is possible under this test (due to the variety of sensor sampling systems) and, therefore, the selected sites shall meet the minimum concentration range for the pollutant under test as defined in Table 5. The selection of test sites should be undertaken to ensure there is a high probability that the required range of concentrations is met. Sensors with multiple pollutant measurements may require multiple test sites to ensure the concentration ranges are achieved for all pollutants. In addition, the PM₁₀ evaluation should have a high percentage of coarse particulate matter and the site selected should have an average value of (PM₁₀-PM_{2.5})/PM₁₀ greater than 0.3 during the month prior to the field evaluation.

9.6.1 Site Installation:

9.6.1.1 Test sensors are installed outside and mounted side by side and within 3 m of the sampling inlet of the reference instrument used to measure the concentration of pollutants of interest. The reference instrument is operated according to internationally recognized best practice for ambient air monitoring instruments as defined in regulations such as the US 40 CFR Part 58, 2008/50/EC of the European Union or Practice D3249 to ensure reliable performance.

9.6.1.2 After installation of the sensors, their operation shall be verified as satisfying all criteria stated in the manufacturer’s manual. The sensor data clock is synchronized to that of the monitoring station or reference instrument as appropriate. The sensors are first calibrated according to 9.6.2. The sensor readings are not adjusted during the period of the field test. The field test is for a period of 6 weeks, not including the calibration week. If the range of concentrations during the field test does not meet the maximum and minimum bounds as defined in Table 5, the test shall continue until the requirement is achieved and the last 6 weeks of data shall be used. If the concentration range is not met in a reasonable period of time, a new site can be selected and the field test restarted. The week prior to the last 6 weeks of data shall be the calibration week. Routine maintenance and replacement of consumables shall be

⁸ Kottke, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., “Worldmap of the Köppen-Geiger climate classification up-dated,” *Meteorol Z*, Vol 15, 2006, pp. 259–263.

⁹ <http://koeppen-geiger.vu-wien.ac.at/> (Accessed 26 May 2021).

TABLE 4 Main Climate Types According to the Köppen-Geiger Climate Classification Scheme

Climate Type	Description
A	Equatorial
B	Arid
C	Warm temperate
D	Snow
E	Polar

TABLE 5 Hourly Average Pollutant Concentrations Required at a Field Test Site

	SO ₂ nmol/mol	NO ₂ nmol/mol	O ₃ nmol/mol	CO μmol/mol	PM _{2.5} μg/m ³	PM ₁₀ μg/m ³
Maximum	≥20	≥50	≥50	≥5	≥50	≥50
Minimum	≤2	≤5	≤5	≤0.5	≤5	≤5

performed according to the manufacturer instructions and these actions shall be noted in the field test report.

9.6.2 *Field Calibration:*

9.6.2.1 Calibration of the test sensors shall occur during the week prior to the start of each field test by comparing averaged hourly data from the test sensor and co-located reference instrument. It is assumed that the test sensors and the monitoring station data can be described by a linear relation and the slope and intercept are estimated using linear regression (Practice E3080). The values for the slope and intercept obtained during the calibration period should be noted in the test report for each parameter and applied to the sensor field data collected during the period of the test prior to the calculation of any test results. The week of data used for calibration is not to be included in the calculation of test results.

9.6.3 *Data Validation and Treatment of Outliers:*

9.6.3.1 Outlying observations in the sensor data is treated according to Practice E178. This outlines the process for rejection if a physical reason for the outlier is known, and the use of statistical tests if the reason for the outlier is unknown. If an outlier in one of the sensors under test is suspected the paired sensor (x_{i1}, x_{i2}) data should be subject to a Grubbs tests at the 5 % significance level according to Practice E178 using x_i as the test sample,

where:

$x_i = |x_{i1} - x_{i2}|$, the absolute difference between paired sensor data points
 x_{i1} = the i th value from sensor 1 and,
 x_{i2} = the i th value from sensor 2.

9.6.3.2 The Grubbs test can be applied to multiple outliers in a recursive manner according to Practice E178 until a maximum of 5 % of the data is removed.

9.6.3.3 The data set after removal of any outliers should be considered the validated data set and used to calculate the averages for the field test calculations. A validated hourly average can be calculated if >75 % of the sensor data logged in the hour is valid.

9.6.4 *Field Reproducibility:*

9.6.4.1 For gases, the field reproducibility is calculated from the standard deviation of measured hourly average data from the two sensors over the entire field test period. For PM_{2.5} and PM₁₀, the field reproducibility is calculated from the standard deviation of 24 hourly average data from the two sensors over the entire field test period.

9.6.4.2 The field reproducibility standard deviation ($S_{r,f}$) in % is calculated according to:

$$S_{r,f} = \sqrt{\frac{\sum_{i=1}^n (X_{1,i} - X_{2,i})^2}{2n}} \times 100 \quad (18)$$

where:

X_{1i} = the i th measurement result of test unit 1,
 X_{2i} = the i th measurement result of test unit 2,
 n = the number of parallel measurements, and
 c = the average concentration of the pollutant measured during the field test by the reference instrument.

9.6.5 *Data Capture Rate:*

9.6.5.1 The data capture rate (DCR) of the field test period is calculated as:

$$DCR = \frac{t_u}{t_i} \times 100 \quad (19)$$

where:

t_u = the total time period with validated data measured in hours, and
 t_i = the total time period of the field test minus the time for routine maintenance measured in hours.

9.6.6 *Field Comparability:*

9.6.6.1 *O₃, NO₂, CO, SO₂, and Other Gaseous Pollutants:*

(1) Plot the hourly average measurements obtained with each sensor against the corresponding hourly average measurements obtained with the reference instrument. Calculate the linear regression slope and intercept and the coefficient of determination (r^2) (Practice E3080). Calculate the mean absolute error (MAE) using the hourly averaged data according to:

$$MAE = \frac{\sum_{i=1}^n |y_i - x_i|}{n} \quad (20)$$

where:

y_i = the i th measurement result of the sensor under test,
 x_i = the i th measurement result of the reference instrument, and
 n = the number of parallel measurements.

(2) Calculate the root mean square error (RMSE) using the hourly averaged data according to:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{n}} \quad (21)$$

where:

y_i = the i th measurement result of the sensor under test,
 x_i = the i th measurement result of the reference instrument, and
 n = the number of parallel measurements.

(3) Calculate the normalised root mean square error (nRMSE) using the hourly averaged data according to:

$$nRMSE = \frac{RMSE}{\bar{x}} \quad (22)$$