

Specifying Calibration of Environmental Sensors

September 2020

(This page intentionally left blank)

Specifying Calibration of Environmental Sensors

Jason Tuenge, Michael Poplawski, and Benjamin Feagin Jr., Pacific Northwest National Laboratory

September 2020

Produced for the U.S. Department of Energy, Energy Efficiency and Renewable Energy, by the Pacific Northwest National Laboratory, Richland, Washington 99352

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <<https://www.ntis.gov/about>>
Online ordering: <http://www.ntis.gov>

Abstract

The emergence of the Internet of Things is resulting in an increased ability of devices and systems to share data and is generating increasing interest in integrating sensors into a variety of devices deployed in the built environment. The value of such data is a function of how the data can be used. Data-producing devices and systems that enable valuable use-cases in turn can be seen as more valuable. Lighting systems are particularly interesting platforms for integrated sensors. Both indoor and outdoor lighting devices are becoming more connected, and their location is often ideally suited for hosting environmental sensors that can characterize the properties of indoor or outdoor spaces in ways that support a wide variety of use cases, from improving air quality to supporting fault diagnostics and prediction. The value of environmental-sensor-driven use-cases and the lighting systems that house them is dependent to some degree on sensor accuracy.

Environmental sensors utilize a wide variety of sensing techniques or technologies and have varying accuracy. More-accurate, laboratory-grade products or reference standards are often used to characterize, refine, calibrate, adjust, and monitor devices that are deployed, or are intended to be deployed, in physical spaces of interest. Sensors or reference standards need to be calibrated periodically to ensure that their use yields accurate measurements. Calibration needs, however, vary in sophistication, based on user and use-case requirements. This paper provides guidance for evaluating the performance of environmental sensors so as to ensure that they meet user or use-case needs. It describes best practices that have been developed for a) calibrating sensors to ensure some known level of accuracy, and b) determining whether calibration-laboratory accreditation meets user or use-case needs. Excerpts from laboratory scopes of accreditation are shared to reveal the diversity of terminology and format among them. In an effort to aid those who currently have sensors calibrated or who have new or changing needs for sensor calibration, rationale is provided for why a specification might be used to request calibration services that meet specific needs.

Commercially available calibration-service providers that are accredited for environmental-sensor calibration are compared and contrasted, and a specification template that might be used for requesting this calibration is presented. The specification template should be tailored to meet each user's needs. To illustrate, an example set of environmental-sensor test conditions (reflecting the planned usage of the device to be calibrated) is used to develop a customized calibration specification, and commercially available service providers are assessed in terms of their qualifications for calibration to that particular implementation of the specification template.

Introduction

Environmental sensors are used to characterize properties of indoor or outdoor spaces, such as temperature, humidity, or air quality. Such sensors are used for many purposes. They are commonly used to determine whether the heating, ventilation, and air conditioning (HVAC) systems that condition indoor spaces are delivering the target level of service. Sensors are installed in outdoor spaces to monitor the impacts of, for example, automobile traffic, manufacturing byproducts, or weather on air quality. Emerging systems that are capable of detecting fault conditions can use environmental sensor data to aid in diagnose (i.e., identify the root cause) and possibly predict the future occurrence of faults. The emergence of the Internet of Things (IoT) from primarily industrial applications into more-mainstream applications has led to the growing integration of low-cost environmental sensors into a wide array of end-use devices, including indoor lighting fixtures and outdoor streetlights.

Commercially available sensors utilize a wide variety of sensing techniques or technologies and characterize properties with varying accuracy. More-accurate, laboratory-grade products or reference standards are often used to characterize, refine, calibrate, adjust, and monitor devices that are deployed, or are intended to be deployed, in physical spaces of interest. Sensors or reference standards need to be calibrated periodically to ensure that their use yields accurate measurements. Specifically, calibration helps to improve trueness by minimizing systematic error (e.g., due to instrument bias), as opposed to improving precision by minimizing

random error (e.g., due to variation attributable to different operators). However, calibration does enable quantification of measurement uncertainty. International Organization for Standardization (ISO) standard 5725-1:1994 provides definitions for accuracy, trueness, precision, and related terms (ISO 1994).

Calibration needs vary in sophistication, based on user and use-case requirements. At one extreme, the user of a measuring instrument (i.e., measuring equipment) may only want or need a rough sense of a measured quantity, the instrument may exhibit relatively poor resolution and precision, and the user may never have the instrument calibrated. While such a situation might suffice, for example, when a lighting design comfortably meets requirements, it can pose problems when little room is left for measurement error, and a code inspection by the local authority having jurisdiction determines that illuminance is noncompliant. At the next level of sophistication, the user may have the instrument calibrated periodically but does not use specifications to ensure that the calibration laboratory (i.e., calibration service provider) is qualified and that the calibration will cover the range of intended use. In this case, the calibration might reduce measurement uncertainty but won't necessarily ensure an established or expected level of measurement trueness. A sophisticated user will develop specifications for calibration that cover the range of intended use but will also ensure that the laboratory is qualified to calibrate the measuring equipment.

Government agencies (which must ensure that outdoor air quality meets regulatory requirements) and manufacturers of devices that characterize properties of indoor or outdoor spaces are examples of entities that may be more sophisticated in terms of calibration requirements. Such entities may have a small set of devices calibrated periodically to serve as internal reference standards, and then may use these to calibrate environmental-sensing devices that will be sold or otherwise put into service, thereby ensuring a degree of accuracy in the field.

Background

Previous work, focused on specifying calibration of energy-measurement equipment, provided some background on measurement science (i.e., metrology) and metrological traceability, and reviewed calibration terminology and standards (Tuenge et al. 2020).

Many types of environmental sensors exist, varying in the quantity measured or the measurement principle used for a given quantity. This paper explores available means of calibration for equipment used to measure the following quantities:

- Dry-bulb temperature (DBT)
- Relative humidity (RH)
- Carbon dioxide (CO₂)
- Total volatile organic compounds (TVOC)
- Particulate matter (PM) with diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5})

The following four sections provide background on relevant criteria and test methods for these quantities.

DBT and RH

RH is the amount of water vapor present in air, expressed as a percentage of the amount needed for saturation at the same DBT. Assuming slow air movement (less than 40 cubic feet per minute) and 50% RH, the "operative temperatures" recommended in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [Standard 55-2017](#) range from 68.5 °F to 75 °F in winter, and from 75 °F to 80.5 °F in the summer, with recommended RH of $\leq 65\%$ (National Institute for Occupational Safety and Health [NIOSH] 2015). This aligns with Section III, Chapter 2, Subsection V of the *U.S. Occupational Safety and Health*

Administration (OSHA) Technical Manual, which recommends 68 °F to 76 °F DBT and 20% to 60% RH for office environments (OSHA 2020). Air Feature 16 ([Humidity Control](#)) of the voluntary WELL Building Standard further recommends restricting RH to a range of 30% to 50% (WELL 2020). Although conditions are not so tightly controlled in some environments (e.g., warehouses), the characteristics (e.g., accuracy) of test equipment and test specimens often depend on DBT or RH, so it can be important to record these values during testing. In fact, many test methods specify permissible ranges for DBT or RH. For example, section 3.3.2 ("reference temperature and humidity") of American National Standards Institute (ANSI) standard C12.1-2014 (NEMA 2016) specifies an ambient temperature of 23 °C with RH ≤ 80% noncondensing; no tolerance for temperature is specified in that section, but some other sections specify 23 °C ± 5 °C (corresponding to a range of 64.4 °F to 82.4 °F). The required measurement range for both quantities will ultimately depend on the use case (e.g., local conditions).

CO₂

In Table Z-1 of [29 CFR 1910.1000](#), OSHA specifies the permissible exposure limit (PEL) for worker exposure to CO₂ as an eight-hour time-weighted average (TWA) of 5,000 parts per million (ppm). By way of comparison, OSHA also requires that compressed breathing air meet the requirements for Grade D breathing air described in ANSI / Compressed Gas Association (CGA) Commodity Specification for Air, G-7.1-1989, including a CO₂ concentration of ≤ 1,000 ppm [[29 CFR 1910.134\(i\)\(1\)\(ii\)\(D\)](#)]. To ensure that most space occupants will be satisfied with respect to human body odor, informative Appendix D to ASHRAE Standard 62.1-2016 recommended maintaining a concentration of steady-state CO₂ (as a proxy for bioeffluents) of ≤ about 700 ppm above outdoor air levels, which typically range from 300 ppm to 500 ppm in acceptable outdoor air; however, this appendix was removed via an addendum in 2018 (ASHRAE 2019). WELL's Air Feature 3 ([Ventilation Effectiveness](#)) similarly specifies a steady-state CO₂ concentration of < 800 ppm for spaces ≥ 46.5 m² (500 ft²) with occupant density > 25 people per 93 m² (1,000 ft²). Meanwhile, WELL's Air Feature 18 ([Air Quality Monitoring and Feedback](#)) specifies a resolution of 25 ppm or finer (i.e., smaller) for reported CO₂ concentration, citing the U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) v4 *Reference Guide for Building Design and Construction* (BD+C), Indoor Environmental Quality (EQ) prerequisite for Minimum Indoor Air Quality Performance.

TVOC

TVOC inexpensively gauges the total concentration of multiple (as opposed to all) volatile organic compounds (VOCs) expected to be present in the air; different TVOC measurement methods can yield substantially different values (e.g., due to the mixture of VOCs present), and appropriate thresholds for individual VOCs in the mixture can vary widely, so the total concentration is only useful in broadly detecting the presence of potentially unhealthy pollutants – which would then motivate more-granular monitoring using more-specialized sensors (LBNL 2020). Indeed, research has not shown TVOC to be a useful metric for health and comfort effects in buildings, and there is insufficient scientific basis for establishing thresholds for TVOC (Andersson et al. 1997). WELL's Air Feature 1 ([Air Quality Standards](#)) limits TVOC concentrations to < 500 µg/m³ and includes a limit for the VOC formaldehyde of < 27 parts per billion (ppb), citing the LEED v4 *Reference Guide for BD+C* EQ credit for Indoor Air Quality Assessment for both criteria (but providing a time interval for neither). By way of comparison, the OSHA PEL for formaldehyde is ≤ 0.75 ppm (750 ppb) as an eight-hour TWA ([29 CFR 1910.1048\(c\)\(1\)](#)).

PM_{2.5}

The U.S. Environmental Protection Agency (EPA) has established definitions and limits for PM in Title 40 of the Code of Federal Regulations (CFR), and background is provided on the EPA website (EPA 2020). In 40 CFR part 58, PM_{2.5} is defined as PM with a nominal aerodynamic diameter ≤ 2.5 µm ([40 CFR 58.1](#)). Table 2 in its Appendix G provides concentration limits for PM_{2.5} and four other pollutants; the 24-hour average PM_{2.5} limits for six Air Quality Index (AQI) categories are as follows: 12.0 µg/m³ for Good, 35.4 µg/m³ for Moderate, 55.4 µg/m³ for Unhealthy for Sensitive Groups, 150.4 µg/m³ for Unhealthy, 250.4 µg/m³ for Very Unhealthy, and 350.4 µg/m³ for Hazardous. The AQI maps ambient concentrations to a scale from 0 to 500,

keyed to the National Ambient Air Quality Standards (NAAQS), and the index value of 100 (high end of Moderate range) is associated with the numerical level of the short-term standard (i.e., averaging time of 24 hours). Whereas the primary annual $\text{PM}_{2.5}$ standard is met when the annual arithmetic mean concentration is $\leq 12.0 \mu\text{g}/\text{m}^3$, the primary 24-hour $\text{PM}_{2.5}$ standard is met when the 98th percentile 24-hour concentration is $\leq 35 \mu\text{g}/\text{m}^3$ ([40 CFR 50.18](#)). Meanwhile, [Table C-4 to subpart C of 40 CFR part 53](#) specifies an acceptable range of $3 \mu\text{g}/\text{m}^3$ to $200 \mu\text{g}/\text{m}^3$ mass concentration for $\text{PM}_{2.5}$, to enable comparison of candidate equivalent methods and reference methods. $\text{PM}_{2.5}$ thresholds are geared toward [outdoor](#) applications but are also applicable indoors (WHO 2010, Mannshardt et al. 2017). The outdoor "range to expect" for 24-hour $\text{PM}_{2.5}$ in the U.S. is $0 \mu\text{g}/\text{m}^3$ to $40 \mu\text{g}/\text{m}^3$ (Williams et al. 2014).

WELL's Air Feature 1 ([Air Quality Standards](#)) limits $\text{PM}_{2.5}$ concentration to $< 15 \mu\text{g}/\text{m}^3$ (without specifying time interval), citing the NAAQS. But whereas the EPA's limits for PM are based on mass concentration – i.e., the number of particles per unit volume (Castell et al. 2017). For example, WELL's Air Feature 18 ([Air Quality Monitoring and Feedback](#)) specifies a resolution of $\leq 35,000$ counts per m^3 (1,000 counts per ft^3) for particle count concentration, or $\leq 10 \mu\text{g}/\text{m}^3$ for particle mass concentration. Similarly, OSHA specifies in Table Z-1 of 29 CFR 1910.1000 an eight-hour limit for a Particulates Not Otherwise Regulated (PNOR) respirable fraction of ≤ 15 ppm, where respirable fraction is generally for PM with a nominal aerodynamic diameter $\leq 10 \mu\text{m}$, i.e., PM_{10} (OSHA 2013).

Calibration of Environmental Sensors

Accreditation bodies (ABs) that are International Laboratory Accreditation Cooperation (ILAC) Mutual Recognition Arrangement (MRA) signatories have been peer-evaluated in accordance with the requirements of International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 17011 to assess and accredit conformity-assessment bodies according to relevant international standards; for example, calibration laboratories are assessed using ISO/IEC 17025. The five U.S.-based ILAC MRA signatories that accredit calibration laboratories are the American Association for Laboratory Accreditation (A2LA), the ANSI National Accreditation Board (ANAB), the International Accreditation Service (IAS), the National Voluntary Laboratory Accreditation Program (NVLAP), and Perry Johnson Laboratory Accreditation (PJLA). Numerous manufacturers offer calibration services; of these, some use equipment calibrated by an accredited laboratory, and fewer are themselves accredited to perform the calibrations. It is also common for manufacturers to only offer calibration services for equipment they produce.

Calibration and measurement capabilities (CMCs) for which each calibration laboratory is accredited by an AB are documented in the laboratory's scope of accreditation, which is published on the AB's website (to aid finding a suitable calibration laboratory), and often on the laboratory's website (where it serves as a brochure of sorts) as well. Scopes of accreditation vary substantially in terms of format and content. Information is typically presented in tables with four (or occasionally five) columns and multiple rows, where each row presents a distinct CMC. Column content varies between ABs, between calibration laboratories accredited by any given AB, and even within a given laboratory's scope of accreditation. However, column content is generally as follows:

- Column 1 describes the [quantity](#) (i.e., property) of interest and typically clarifies whether it is being sourced (i.e., generated, output, produced) or measured by the equipment being calibrated. Sometimes test conditions for other quantities are provided here as well (e.g., ambient temperature range when CMC is for humidity).
- Column 2 describes the range(s) over which CMC uncertainty has been determined. These ranges typically pertain to the quantity being calibrated but often also include test conditions for other quantities.

- Column 3 states the uncertainty for the CMC. This uncertainty is understood to be the best (i.e., smallest or lowest) value achievable by the laboratory, and this value (or formula) is valid across the stated range; the laboratory cannot claim a smaller uncertainty for the CMC on calibration certificates (ILAC 2013). When multiple ranges are given, each uncertainty shown is the smallest achievable by the laboratory over the corresponding range.
- Column 4 describes the test method/procedure, the equipment used to perform the calibration, or both (ILAC 2013, A2LA 2020). Some scopes of accreditation leave this column empty; in such cases, it is particularly important to seek clarification from both the laboratory and the AB regarding the applicable test method and calibration equipment. Notably, in addition to the best CMC that is explicitly addressed in the scope of accreditation, the laboratory may have multiple other implementations of the CMC that are nonetheless covered by the accreditation, albeit at larger uncertainties; for example, specific calibration equipment might be listed in the document, but other equipment might be used instead (ILAC 2010).

Scopes of accreditation for calibration laboratories typically distinguish between calibration of quantity-measuring equipment and calibration of equipment that produces or provides a quantity. However, these documents can be difficult to interpret, as the relevant terminology has not been harmonized:

- When calibrating temperature-measuring equipment, for example, coverage is clearest if the scope of accreditation states "temperature-measuring equipment" or "equipment to measure temperature" in the first column for a CMC. The terms "temperature – source" and "temperature – generate" are less clear but also acceptable (and very common). It is unlikely that calibration of temperature-measuring equipment is covered if the scope of accreditation only states "temperature – measure" in the first column (i.e., with no CMC for "temperature – source" or "temperature – generate" or "temperature-measuring equipment"). In this case, it would be advisable to seek confirmation from both the calibration laboratory and its AB, and to request documentation detailing the test method or procedure (e.g., showing how a reference probe is used in an environmental chamber that is not described in the scope of accreditation).
- When calibrating temperature-generating equipment, coverage is clearest if the scope of accreditation states "temperature-generating equipment" or "equipment to generate temperature" (or substitute "sourcing" for "generating" and "source" for "generate" in these two phrases) in the first column for a CMC. The term "temperature – measure" is less clear but also acceptable (and very common).
- If a CMC is only described as "temperature" in the first column, it is not immediately clear whether the laboratory is accredited to calibrate temperature-sourcing equipment, temperature-measuring equipment, or both. However, make/model information for the calibration equipment is often provided in the last column of the CMC, and this might provide clarity. In any case, it would be advisable to seek confirmation from both the calibration laboratory and its AB.

The three-year grace period for laboratory compliance with ISO/IEC 17025:2017 expires in November 2020 (ILAC-ISO 2017). Similarly, the three-year grace period for scopes of accreditation to comply with ISO/IEC 17011:2017 expires in November 2020 (IAF-ILAC 2017). Consequently, some scopes of accreditation updated after November 2017 may not yet reflect compliance with the 2017 versions of these standards. For example, many labs still do not state the method/procedure or calibration equipment in their scope. ILAC-P14:01/2013 states that a scope of accreditation must – for each CMC – state the method/procedure, the calibration equipment, or both (ILAC 2013). In contrast, ISO/IEC 17011:2017 now requires both of these elements to be present (IEC 2017).

Section 2.2. of ILAC-G18:04/2010 permits some flexibility if the scope of accreditation is explicitly flexible (e.g., regarding analytes and methods) but does not allow flexibility regarding quantities or measurement principles (ILAC 2010). Section 2.1 of the same document suggests that, even if the scope is not explicitly

flexible, range and uncertainty can be omitted from the scope of accreditation. In contrast, section 5.1 of ILAC-P14:01/2013 stipulates that range and uncertainty be stated for each CMC.

Below are four sections that discuss calibration of equipment used to measure DBT, RH, CO₂, TVOC, or PM_{2.5}. General considerations from these discussions include the following:

- The search tool on the NVLAP website did not function properly when search terms included numerals (e.g., CO₂ or PM_{2.5}), and the site is not searchable via Google, so some laboratories accredited by this AB for such calibrations likely escaped detection by the authors.
- EPA gives requirements in [Appendix B to 40 CFR, part 60](#), for continuous emission monitoring systems (CEMS) in "stationary sources" such as smokestacks to measure concentrations of CO₂ ([Performance Specification 3](#)), TVOC ([Performance Specification 8](#)), and PM_{2.5} ([Performance Specification 11](#)). However, such applications typically differ greatly from indoor environments in terms of concentration and flow rate.
- Local environmental conditions (e.g., temperature, humidity, airborne pollutants) can affect sensor accuracy, so field calibration may be preferred when laboratory calibration is performed under conditions that are not representative (Maag et al. 2018). Field calibration via comparison with collocated reference equipment can be more advantageous in terms of cost and accuracy; for example, by accounting for local conditions not reflected in a controlled laboratory environment (Spinelle et al. 2017f, Kim et al. 2018, Forbes 2020). However, such reference equipment is itself costly and not always available. In addition, field tests with uncontrolled temperature and humidity can make it impossible to distinguish between their respective effects on sensor response (Spinelle et al. 2017f). Researchers have in recent years developed environmental chambers capable of regulating pollutant levels in addition to temperature and humidity (Omidvarborna et al. 2020), and similar calibration equipment may soon appear in laboratory scopes of accreditation. Field calibration can sometimes be effectively done with forced air or diffusion-based reference sources. Notably, these methods invariably disturb the local environment and are thus imperfect.

DBT and RH

Although some devices only measure DBT or RH, many measure and report both quantities simultaneously. It is fairly common for the rated accuracy of measuring equipment to be a function of ambient DBT or RH, so calibration is ideally performed across a set of quantity values, where different combinations are achieved by independently varying each of the two quantities. Some devices mate with calibration equipment produced by the same manufacturer, or with equipment designed to the same compatibility standard. Devices that are not designed to be used with such calibration equipment are best calibrated in the field via comparison with a reference meter, or by calibration laboratories that are accredited to calibrate such equipment in environmental (i.e., exposure) chambers. The CMC should state the covered temperature and humidity ranges, as well as any requirements for compatibility with calibration equipment (e.g., make/model information for the environmental chamber).

Table 1 provides excerpts from example scopes of accreditation for U.S. laboratories suitable for calibration of DBT- and RH-measuring equipment in environmental chambers, found via online searches (using AB websites and Google) for documents that contained the term "humidity" (the resulting set was then searched locally for the term "temperature"). Notably, none of these scopes of accreditation distinguish between DBT and wet-bulb temperature; similarly, some only state "humidity" (in lieu of the more specific "relative humidity") in the first column of the CMC, although "RH" is often used to describe the range. In addition, two of the examples state one or more temperature ranges for the humidity CMC. Three of the examples state the make/model of the calibration equipment, thereby enabling review of product data sheets and user manuals; for example, to confirm that the internal dimensions will accommodate the equipment to be calibrated.

CO₂

Although a gas chromatograph - mass spectrometer (GC-MS) could be used to identify gases and quantify their relative abundance in the surrounding air mixture, it is more typical to use one or more relatively inexpensive sensors that are each calibrated to yield maximum response for a particular gas of interest (while also inadvertently exhibiting some response to other gases). Non-dispersive infrared (NDIR) sensors are typically used for CO₂ monitoring (Maag et al. 2018, Hayat et al. 2019). Temperature affects NDIR sensor accuracy, and some equipment features automatic compensation (Alphasense 2014). In contrast, humidity does not independently (of temperature) affect the accuracy of some (but perhaps not all) NDIR sensors (Kim et al. 2018). Consequently, calibration would ideally be performed across multiple temperature points; for example, in an environmental chamber. Some NDIR-based equipment incorporates a pump, which can then be used for calibration (and which may be required by some laboratories for compatibility). Other NDIR-based equipment relies on diffusion in lieu of a pump, and must be calibrated without forced air; for example, in the field (i.e., on site) via comparison with collocated reference equipment (Sensirion 2018).

Table 2 provides excerpts from example scopes of accreditation for U.S. laboratories explicitly suitable for calibration of CO₂-measuring equipment, found via online searches for documents that contain "CO₂" and related terms (i.e., "carbon dioxide," "dioxide"). Notably, the calibration equipment for the first example includes an air-quality monitor, and the fourth example does not explicitly cover calibration of equipment used to measure CO₂ concentration; none of these CMCs explicitly entail the use of an environmental chamber. Also, some of the ranges include zero values (which may not be truly realizable in practice, given that negative values are not possible). Also note that CMCs often do not state balance gases, or their relative proportions, for the calibration gas mixture; this should be clarified (and specified) prior to calibration. The balance gas is often nitrogen alone; if, instead, it is a standard combination of gases to represent air (e.g., ANSI/CGA G-7.1 Grade D), then the CO₂ content of the balance-gas mixture must also be known. ILAC G18 permits flexibility concerning parameters or analytes in scopes of accreditation that are explicitly flexible, provided that the same measurement principles are used; an example would be the extension of O₂ calibration via GC-MS to calibration of other gases (e.g., CO₂) using this same method.

TVOC

VOCs can also be accurately measured via GS-MS, other methods are desirable for field use for reasons similar to those discussed for CO₂. Photoionization detection (PID) sensors are relatively inexpensive and not particularly selective (they ionize anything having an ionization potential at or below the lamp-output voltage), so they are commonly used to measure TVOC concentration (Williams et al. 2015, Spinelle et al. 2017r). However, recent studies have cast doubt on the accuracy (both trueness and precision) of low-cost TVOC-measuring equipment (Goletto et al. 2020). Meanwhile, NDIR sensors can sometimes be used to detect infrared-absorbing VOCs such as methane (Szulczyński et al. 2017).

ISO 16000-29:2014 specifies test methods and performance requirements for VOC detectors (which incorporate sensors that in turn incorporate sensing elements) that are designed to monitor indoor concentrations of one or more VOCs (ISO 2014); these detectors can be of aspirated (actively pump-driven) or diffusion-type (passive) design. However, the methodology has been deemed by some researchers as inapplicable for formaldehyde detectors and too demanding for connected field devices; the American Society for Testing and Materials (ASTM) is currently developing a new standard (Goletto et al. 2020).

Laboratory calibration of TVOC-measuring equipment typically uses isobutylene as the reference gas, with nitrogen or air as the balance in the mixture; another compound, such as toluene, benzene, or formaldehyde, may be used as the reference gas (i.e., calibration gas) in some cases (Mizukoshi et al. 2010, Williams et al. 2015, Goletto et al. 2020). Response factors (i.e., correction factors) are calculated as the true VOC concentration divided by the indication (i.e., reading) from the PID, or equivalently as a reading for calibration gas divided by a reading for the same concentration of a specific VOC (RAE Systems 2013). These multipliers are published in tables by PID-based equipment manufacturers. If only one VOC is known to be present, then the response factor can be applied to a reading (which, before adjustment, denotes calibration-gas

concentration) to yield the concentration of that VOC. If the response factor for a given compound is > 1.0 , the PID is more sensitive to the reference gas; if it is < 1.0 , the PID is less sensitive to the reference gas. For example, if a PID is twice as sensitive to toluene as it is to isobutylene, its response factor for toluene is 0.5 (relative to isobutylene).

Table 3 provides excerpts from example scopes of accreditation for U.S. laboratories suitable for calibration of TVOC-measuring equipment, found via online searches for documents that contain "TVOC" and related terms (i.e., "VOCs," "isobutylene," " C_4H_8 "). No CMCs were identified that explicitly covered "TVOC" in the first column. Ranges for all three examples are for the same concentration of 100 ppm (which is a single value rather than a range). However, the first example implies that calibration is for "total organics" relative to isobutylene (rather than for isobutylene concentration alone). In addition, only the third example explicitly covers calibration of equipment used to measure concentration. Notably, calibration equipment for the first example includes a PID. None of these CMCs explicitly entail use of an environmental chamber.

PM_{2.5}

The EPA has a program to evaluate instruments suitable for use in determining compliance with the NAAQS (EPA 2011, Williams et al. 2018). Candidate instruments measuring PM_{2.5} that satisfy the applicable NAAQS performance specifications in 40 CFR, parts 50 and 53, are designated as "methods" – either a Federal Reference Method (FRM) or a Federal Equivalent Method (FEM). A list of designated air-monitoring FRMs and FEMs for the six Criteria Pollutants (EPA 2017) is published by the EPA on its Ambient Monitoring Technology Information Center (AMTIC) [website](#).

Low-cost PM_{2.5} monitors commonly use light scattering to measure particle concentration (Jovašević-Stojanović et al. 2015, Karagulian et al. 2019). For example, optical particle counters (OPCs) are often used to measure number concentration, which is then converted to mass concentration based on assumptions regarding particle shape and particle density (Castell et al. 2017, Wang et al. 2020). Humidity and, to some extent, temperature can affect OPC sensor accuracy (Maag et al. 2018, Karagulian et al. 2019, Forbes 2020, Han et al. 2020).

Online searches (using AB websites and Google) for calibration-laboratory scopes of accreditation that contain "PM_{2.5}" and related terms (i.e., "particulate," "particle," "aerosol") only yielded hits where the accreditation covered calibration of particle counters or calibration for number concentration (as opposed to mass concentration). Many laboratories are accredited to calibrate aerosol-particle counters for particle detection, counting efficiency, size, size resolution, or flow (none of which pertain to concentration). None are accredited for calibration of low-cost PM_{2.5}-measuring equipment (Omidvarborna et al. 2020).

The first example in Table 4 is an excerpt from the only scope of accreditation identified by the authors that explicitly covers calibration by a U.S. laboratory for aerosol-particle concentration. Note that it applies to number concentration (rather than mass concentration). In addition, the word "measure" (unaccompanied by the word "equipment") typically means that the CMC pertains to calibration of equipment that produces (i.e., sources or generates) a given concentration, so it is unlikely to cover calibration of equipment used to measure number concentration. The second example explicitly covers calibration of particle counters; it is not likely that the quantity covered is number concentration or mass concentration. None of these CMCs explicitly entail use of an environmental chamber.

Laboratory calibration of low-cost sensors can fail to ensure agreement with reference PM_{2.5} monitors if the range of local conditions (e.g., DBT and RH) is not covered (Castell et al. 2017). Consequently, low-cost sensors are often calibrated in the field via comparison with reference equipment (where available). However, researchers have introduced increasingly flexible environmental chambers in recent years (Papapostolou et al. 2017, Sayahi et al. 2019, Tryner et al. 2020, Omidvarborna et al. 2020).

Whereas PM_{10-2.5} is defined as particulate matter with an aerodynamic diameter of $\leq 10 \mu\text{m}$ and $> 2.5 \mu\text{m}$ (and that thus has a realizable nonzero lower bound), PM_{2.5} has a lower bound of zero. Given that detector sensitivity can vary with particle size, it might be appropriate to specify a lower bound on particle size for calibration. For comparison, the "typical" particle-size range measured according to ISO 21501-4:2018 is between 0.1 μm and 10 μm (ISO 2018). Instruments that conform to this standard are used in classifying air cleanliness in controlled environments (e.g., cleanrooms) per ISO 14644-1 and ISO 14644-2, which do not address concentrations of smaller "ultrafine" nanoparticles.

Table 1. Excerpts from example scopes of accreditation that cover calibration of equipment used to measure DBT and RH, illustrating differences in content among laboratories (and their ABs). Notice, for instance, that only examples 3 and 4 here state limits on temperature for the CMC pertaining to RH. Several other examples identified, but not shown here, use a chamber-plus-sensor combination with an upper bound of 80% for RH.

Example (AB)	Example column 1	Example column 2	Example column 3	Example column 4
1 (A2LA)	Parameter/Equipment	Range	CMC (\pm)	Comments
	Temperature – Measuring Equipment	(-10 to 70) °C	0.084 °C	Environmental chamber
	Humidity – Measuring Equipment	(10 to 95) % RH	0.58 % RH	Environmental chamber
2 (A2LA)	Parameter/Equipment	Range	CMC (\pm)	Comments
	Temperature – Measuring Equipment	(-70 to 80) °C	0.27 °C	Optica dew point monitor w/Tenney UTRC-W4F-C environmental chamber
	Relative Humidity – Measuring Equipment	(20 to 50) % RH 50 % RH (50 to 90) % RH	0.78% RH 0.80% RH 0.85% RH	Optica dew point monitor w/Tenney UTRC-W4F-C environmental chamber
3 (ANAB)	Parameter/Equipment	Range	Expanded Uncertainty of Measurement (+/-)	Reference Standard, Method, and/or Equipment
	Temperature – Source	(-10 to 70) °C	0.14 °C + 0.0004 % of reading	Thunder Scientific 2500LT Chamber
	Humidity – Source (15 to 35) °C	(5 to 95) %RH	0.56 %RH + 0.27 % of reading	Thunder Scientific 2500LT Chamber
4 (NVLAP)	Measured Parameter or Device Calibrated	Range	Expanded Uncertainty	Remarks
	Temperature – Source	0 °C to 70 °C	0.00069 °C/°C + 0.036 °C	Thunder Scientific 2500
	Humidity – Generate (0 °C to 35 °C) (35 °C to 50 °C)	10% RH to 95% RH 74% RH to 95% RH	0.5% RH 0.6% RH	Thunder Scientific 2500

Table 2. Excerpts from example scopes of accreditation that cover calibration of equipment used to measure CO₂, illustrating differences in content among laboratories (and their ABs). Notably, the calibration equipment for the first example includes an air-quality monitor, and the fourth example does not explicitly cover calibration of equipment used to measure CO₂ concentration. None of the CMCs clarify the balance gas(es) used, and some of the ranges include zero values (which may not be truly realizable in practice, given that negative values are not possible). None of these CMCs explicitly entail use of an environmental chamber.

Example (AB)	Example column 1	Example column 2	Example column 3	Example column 4
1 (A2LA)	Parameter/Equipment	Range	CMC (±)	Comments
	Gas Detection Equipment – [...] CO ₂	[...] 1000 parts in 10 ⁶	[...] 4%	AQ5000\EVM IAQ indoor air quality monitor with calibration gas
2 (A2LA)	Parameter/Equipment	Range	CMC (±)	Comments
	Gas Detection Equipment – [...] CO ₂	0.05% 0.1% 5% 10%	2.6% 2.5% 2.4% 2.2%	[...] Carbon dioxide
3 (A2LA)	Parameter/Equipment	Range	CMC (±)	Comments
	Gas Detection Equipment – [...] CO ₂	[...] (0 to 20.00)%	[...] 2.1%	Standard gas
4 (ANAB)	Parameter/Equipment	Range	Expanded Uncertainty of Measurement (+/-)	Reference Standard, Method, and/or Equipment
	CO ₂	0.5% CO ₂ 5% CO ₂	0.8% 0.8%	Standard gases
5 (ANAB)	Parameter/Equipment	Range	Expanded Uncertainty of Measurement (+/-)	Reference Standard, Method, and/or Equipment
	CO ₂ Sensors	0% CO ₂ 5% CO ₂ 10% CO ₂	0.2% CO ₂	Certified Gases

Table 3. Excerpts from example scopes of accreditation that cover calibration of equipment used to measure TVOC using isobutylene (C₄H₈) as a proxy, illustrating differences in content among laboratories (and their ABs). No CMCs were identified that explicitly covered "TVOC" in the first column. Ranges for all three examples are for the same concentration of 100 ppm (which is a single value rather than a range). However, the first example implies that calibration is for "total organics" relative to isobutylene (rather than for isobutylene concentration alone). In addition, only the third example explicitly covers calibration of equipment used to measure concentration. Notably, calibration equipment for the first example includes a PID. None of these CMCs explicitly entail use of an environmental chamber.

Example (AB)	Example column 1	Example column 2	Example column 3	Example column 4
1 (A2LA)	Parameter/Equipment	Range	CMC (±)	Comments
	Total Organics Relative to Isobutylene	100 parts in 10 ⁶	3%	MiniRAE 2000 PID (photoionization detector) with calibration gas
2 (ANAB)	Parameter/Equipment	Range	Expanded Uncertainty of Measurement (+/-)	Reference Standard, Method, and/or Equipment
	Isobutylene	0.01% Isobutylene	1.1%	Standard gases
3 (IAS)	Calibration Area	Range	Expanded Uncertainty (±)	Technique, Reference Standard, Equipment
	Gas Detection Equipment – C ₄ H ₈	100 ppm	3.5%	Standard Gas

Table 4. Excerpts from example scopes of accreditation that might (but probably do not) cover calibration of equipment used to measure PM *number concentration*, illustrating differences in content among laboratories (and their ABs). The authors were unable to find any scopes of accreditation covering calibration of equipment used to measure PM *mass concentration* (e.g., for PM_{2.5}). Note that the first example CMC is for measurement, which typically pertains to calibration of equipment used to *produce* number concentration, rather than equipment used to *measure* number concentration. Meanwhile, the second example likely pertains to calibration of equipment used to count particles (it is not likely that the quantity of interest is number concentration). Neither of these CMCs explicitly entail use of an environmental chamber.

Example (AB)	Example column 1	Example column 2	Example column 3	Example column 4
1 (A2LA)	Parameter/Equipment	Range	CMC (\pm)	Comments
	Aerosol Number Concentration – Measure	(0 to 25 000) particles/cm ³	0.80%	Comparison to aerosol electrometer and linearity test w/diluter
2 (ANAB)	Parameter/Equipment	Range	Expanded Uncertainty of Measurement (+/-)	Reference Standard, Method, and/or Equipment
	Optical System – Aerosol Particle Counter	Particle size: (μ m) (0.1, 0.3, 0.5, 1, 2, 5, 10)	6% of reading	Comparison to Standard Particle Counter

Developing Calibration Specifications for Environmental Sensors

When seeking calibration for equipment that sources or measures electrical energy, specifications should be provided to ensure that the calibration will cover the intended use (quantities, ranges, conditions, required accuracy), and that the laboratory is qualified to perform the calibration with sufficiently low uncertainty. Uncertainties for a particular calibration may be substantially worse (larger) than for the best-case scenario reflected in the scope of accreditation, so it is important to request an estimate of the level of uncertainty you can expect for a particular piece of equipment. Further, it cannot be assumed that the laboratory will by default calibrate the measuring equipment across its full range of capability. Similarly, calibration doesn't necessarily include adjustment (BIPM 2008), and adjustment may not be possible for some equipment. Calibration specifications should clarify whether and how equipment should be adjusted if found to be out of tolerance, and should provide sufficient information to allow the calibration laboratory to determine whether the equipment is out of tolerance (according to equipment-manufacturer specifications). If existing specifications are not sufficient, new specifications should be developed. A complete specification will incorporate the following guidelines:

1. The calibration laboratory should be accredited by an ILAC MRA signatory to relevant standards (e.g., ISO/IEC 17025).
2. The laboratory should be explicitly accredited for each particular quantity of interest
 - A. The laboratory should be accredited for the calibration type applicable to the equipment being calibrated. For example, it should be accredited to source (i.e., produce) humidity if calibrating RH-measuring equipment, or should be accredited to measure humidity if calibrating RH-sourcing equipment.
 - B. The range of calibration for which the laboratory is accredited should span the range of quantity values for which the calibrated equipment will be used. For example, if DBT measurements are expected to be in the range of 5 °C to 45 °C, a laboratory accredited to calibrate from 10 °C to 100 °C may not be suitable.
 - C. The range of relevant conditions for which the laboratory is accredited should span the range of conditions under which the calibrated equipment will be used. For example, if RH measurements are expected to be made at DBT values ranging from 5 °C to 45 °C, a laboratory only accredited to calibrate from 15 °C to 35 °C may not be suitable.
 - D. The stated uncertainty for each CMC should satisfy applicable requirements. However, because CMC uncertainties are the smallest achievable by the laboratory, the laboratory should be asked to provide an estimate of the expected uncertainty for the specific equipment to be calibrated.
3. The laboratory should understand the equipment to be calibrated (e.g., should be provided with complete make/model information, including relevant accessories) and the equipment configuration/settings to be used in calibration.
 - A. A given laboratory might only calibrate specific make/model equipment (e.g., if the laboratory is run by a manufacturer) or equipment that meets certain compatibility requirements. Unfortunately, scopes of accreditation typically do not explicitly state such restrictions. However, when specific make/model information is listed for the specific calibration equipment used, product-user manuals may clarify relevant equipment limitations.

- B. The equipment-range settings should be specified to reflect intended usage. Ideally, range settings should maximize resolution; for example, if the minimum range setting for DBT is 10 °C, then a 5 °C calibration point should use this range in lieu of a 100 °C range setting. However, if range settings are not optimized this way in practice, the device should be calibrated accordingly.
- C. The desired calibration interval should also be specified so that it can be stated in the calibration report and thereby help in scheduling future recalibration. The appropriate value will depend on several factors, such as applicable requirements for accuracy as well as on ratings for the equipment being calibrated (rated accuracy can be a function of time since last calibration) and the conditions in which it will be used. Limiting the interval between calibrations is one method of mitigating error due to sensor drift; another is applying corrections between calibrations, based on estimated drift (e.g., according to manufacturer-stated drift specifications). Guidance is offered in ILAC G24:2007 / OIML D 10:2007 (ILAC-OIML 2007), which is jointly published by ILAC and the International Organization of Legal Metrology (OIML). NCSL International similarly provides guidance in its RP-1 (NCSLI 2010).

A specification template for the calibration of DBT- and RH-measuring equipment is presented in Appendix A, and an example implementation of this specification template is presented in Appendix B. Some aspects of specifying the calibration of DBT- and RH-measuring equipment merit additional consideration:

- Zero values can present challenges for calibration. Fundamentally, zero values cannot be realized if negative values are not possible (PJLA 2017). For example, whereas negative values can be realized for temperature units of degrees Celsius, they cannot be realized for units of kelvin. However, it is common to indicate "up to" in lieu of "0 to" on scopes of accreditation (A2LA 2019, ANAB 2019, IAS 2019, PJLA 2017). In addition, the authors found multiple scopes of accreditation with ranges that included zero-percent gas concentration. In any case, if a range includes zero, uncertainty cannot be simply expressed as a percentage of a reading, because the CMC uncertainty can never be zero (IAS 2019).
- In some cases, there may be no laboratory that is accredited across the needed range for every quantity of interest. In such circumstances, it may be acceptable to include some calibration points outside the scope of accreditation; however, this limitation should be clearly noted when presenting data from DBT- and RH-measuring equipment that has been calibrated in this manner.

Summary and Recommendations

The emergence of the Internet of Things is resulting in an increased ability of devices and systems to share data. Interest in specific types of data, and the facilitation of the sharing of those data, are typically driven by use cases, and the performance and value of these use cases are dependent to some degree on the accuracy of those data. Users of such data are encouraged to explore the dependency of the use case on data accuracy, and to ensure that the devices and systems leveraged to implement the use case can deliver data of the requisite accuracy.

The accuracy of data-producing devices can be a function of design, component selection, and manufacturing processes – which may include specific steps aimed at compensating for systematic and/or random error. Manufacturers of data-producing devices, as well as end users with particularly stringent needs, may need to validate or characterize the reporting accuracy of manufactured devices. Such validation or characterization is typically achieved by comparing the data produced by a specific device or set of devices against measurements made by a reference instrument with known or reference accuracy. Such equipment typically needs to be calibrated to establish and maintain this reference accuracy. While many commercial laboratories are accredited to perform such calibrations, their scopes of accreditation vary, and as a result, any given laboratory may or may not be suitable for calibrating a particular instrument for specific reference-measurement uses. The authors offer the following recommendations accordingly:

- Measuring-equipment owners with calibration needs are encouraged to ensure that the calibration will cover the instrument's intended use (quantities, ranges, conditions, required accuracy), and that the laboratory is qualified to perform the calibration with sufficiently low uncertainty. In some cases, the accuracy of measurement for one quantity will depend on the value of another quantity; consequently, it may be advisable to calibrate across a matrix of points at different combinations of values for the quantities. Some service providers (including laboratories) are accredited to calibrate equipment in the field (i.e., on site); field calibration, though limited in range, can provide better accuracy by capturing the background effect of local conditions that differ from a controlled laboratory environment. If existing calibration specifications are not sufficient, new specifications should be developed. Also, measuring equipment should be chosen with an understanding of available options for calibration – some devices are easier to calibrate than others (e.g., due to compliance with compatibility standards), many manufacturers aren't accredited by an ILAC MRA signatory to perform the calibration, some manufacturers only calibrate devices they produce, and a given calibration laboratory may not be accredited to calibrate all quantities measured by a particular multi-sensor device. If equipment has already been acquired, it may be best to acquire another device that's easier to calibrate, and use it (as a reference) to calibrate other equipment in-house.
- Calibration laboratories are encouraged to clearly state scopes of accreditation, including any compatibility requirements. Scopes of accreditation should distinguish between calibration of equipment used to source quantities, and equipment used to measure quantities. Laboratories are encouraged to harmonize terminology and the organization of content within scopes of accreditation, to facilitate more-efficient review by potential customers. Website searches could also be facilitated by adding the text "USA" to scopes of accreditation for laboratories that are located in the U.S.
- ILAC MRA signatories are encouraged to improve their website search tools and make content accessible via external search engines, to facilitate identification of suitable calibration laboratories.

Many use cases for building systems leverage environmental-sensing data. A calibration-specification template for DBT- and RH-measuring equipment was developed as an example of how one might create such specifications for instruments, tailored to their range of expected use. Measuring-equipment owners are encouraged to develop such specifications and share them with potential calibration laboratories to ensure that requirements are met. Once a calibration laboratory is selected and the instrument is calibrated, the

corresponding calibration report should be reviewed to confirm that each calibration point was covered (with acceptable uncertainty), and to determine whether the equipment was out of tolerance. If adjustment was required, it may be necessary to revisit previously measured values, and it may be appropriate to reduce the interval between calibrations.

The authors intend to further develop the provided specification template as needs dictate – perhaps by addressing calibration of measuring equipment incorporating CO₂, TVOC, or PM_{2.5} sensors. Feedback on the existing specification template, and additional suggestions for further development, are encouraged from industry stakeholders with similar needs and interests (email feedback to DOE.SSL.Updates@ee.doe.gov).

Appendices

Appendix A: Specification Template for Calibration of Equipment Used to Measure Temperature and Humidity

Section 1: Specifications for calibration of multi-sensor node

Requirements for calibration of the multi-sensor node described in Section 2 are as follows:

1. Calibration shall be performed by an ILAC MRA signatory-accredited laboratory and within its scope of accreditation to ISO/IEC 17025.
2. Report shall include data for each calibration point as detailed in sections 7.8.2 (common requirements for reports) and 7.8.4 (specific requirements for calibration certificates) of ISO/IEC 17025:2017 (e.g., including uncertainties), with conditions readily discernible from text.
 - A. Report shall indicate calibration interval per manufacturer guidance.
 - B. Report shall express calibration in the form of a calibration table.
 - C. Verification pass/fail (out of tolerance) criteria shall be per the calibrated-equipment manufacturer's accuracy specifications, at the manufacturer-recommended calibration interval.
 - D. If adjustment or repair was required, report shall state that this was performed and provide before/after values (i.e., as-found and as-left).
4. Configuration
 - A. Equipment shall be oriented (*provide additional details here to ensure proper orientation during calibration*).
 - B. Operate (*provide details here regarding modes/settings*).
 - C. See Section 3 for instructions regarding installation and connectivity.
5. Measuring equipment shall be calibrated at the following calibration points:
 - A. Dry-bulb temperature measurement shall be calibrated at the (*specify number here*) points in Table A1.
 - B. Relative-humidity measurement shall be calibrated at the (*specify number here*) points in Table A1.
6. Calibration specifications for the other sensor types (*list here if applicable*) are in development; please exclude them from any price quotes.
7. Adjustment
 - A. The equipment (*indicate "can" or "cannot"*) be adjusted for both temperature and relative humidity; see Section 2 for equipment specifications and Section 3 for adjustment instructions.
 - B. The equipment shall be adjusted if found to be out of tolerance relative to manufacturer accuracy specifications; provide separate quotes for calibration with and without adjustment (*delete bullet if adjustment isn't possible*).

Section 2: Multi-sensor node performance specifications (for reference)

The equipment to be calibrated is a multi-sensor device, manufactured by *(company name here)*, incorporating the sensors described in Table A2.

Access to sensor datasheets and user manuals can be provided separately. The integrated node measures approximately *(quantity value here)* tall, *(quantity value here)* wide, and *(quantity value here)* deep (see *Figure*).

Additional features:

- *(describe connectivity means here; e.g., WiFi)*
- *(describe indication/reading means here; e.g., LCD)*
- *(describe input power means here; e.g., 120 V power supply with 4-foot cord)*

Section 3: Multi-sensor node connectivity, software, and adjustment instructions (for reference)

General notes:

- The information linked from this section pertains to our equipment's software only; for hardware information, see Section 2.

Instructions:

1. *(E.g., describe how to put equipment on the local WiFi network – point to available documentation rather than duplicating it here)*
2. *(E.g., describe how to configure the equipment over the network, again pointing to documentation where available)*
3. *(E.g., describe how to adjust the equipment if it is found to be out of tolerance, again pointing to documentation where available)*

Table A1. Measurement of dry-bulb temperature and relative humidity at 1.0 atm (*revise number of values for each quantity as needed*)

Calibration point	Dry-bulb temperature (°C)	Relative humidity (%)
A. B. C.	(value one) (value two) (value three)	(value one)
D. E. F.	(value one) (value two) (value three)	(value two)
G. H. I.	(value one) (value two) (value three)	(value three)

Table A2. Relevant equipment characteristics

Equipment make/model	Measured quantity	Specs stated on datasheet	Notes
(complete ordering info here)	Dry-bulb temperature	(list performance specs, range, etc.)	
	Relative humidity	(list performance specs, range, etc.)	

Appendix B: Example Specifications for Calibration of Equipment Used to Measure Temperature and Humidity

The following example illustrates the intended use of the specification template provided in Appendix A. A set of nine test cases shown in Table B1 defines the range of intended use of a particular reference environmental sensor. Given the stated range of intended use, the following specifications were developed. Four commercial U.S. calibration laboratories with scopes of accreditation that cover calibration of DBT- and RH-measuring equipment were identified.

Section 1: Specifications for calibration of multi-sensor node

Requirements for calibration and adjustment of the multi-sensor node described in Section 2 are as follows:

1. Calibration shall be performed by an ILAC MRA signatory-accredited laboratory and within its scope of accreditation to ISO/IEC 17025.
2. Report shall include data for each calibration point as detailed in sections 7.8.2 (common requirements for reports) and 7.8.4 (specific requirements for calibration certificates) of ISO/IEC 17025:2017 (e.g., including uncertainties), with conditions readily discernible from text.
 - A. Report shall indicate calibration interval per manufacturer guidance.
 - B. Report shall express calibration in the form of a calibration table.
 - C. Verification pass/fail (out of tolerance) criteria shall be per the calibrated-equipment manufacturer's accuracy specifications, at the manufacturer-recommended calibration interval.
 - D. If adjustment or repair was required, report shall state that this was performed and provide before/after values (i.e., as-found and as-left).
8. Configuration
 - A. Equipment shall be oriented as used, with external probe below unit as shown in Section 2.
 - B. Operate SCD30 in continuous measurement mode, with measurement rate at 2 s.
 - C. See Section 3 for instructions regarding installation and connectivity.
9. Measuring equipment shall be calibrated at the following calibration points:
 - A. Dry-bulb temperature measurement shall be calibrated at the nine points in Table B1.
 - B. Relative humidity measurement shall be calibrated at the nine points in Table B1.
10. Calibration specifications for the other three sensor types (CO₂, TVOC, PM_{2.5}) are in development; please exclude them from any price quotes.
11. Adjustment
 - A. The equipment can be adjusted for both temperature and relative humidity; see Section 2 for equipment specifications and Section 3 for adjustment instructions.
 - B. The equipment shall be adjusted if found to be out of tolerance relative to manufacturer accuracy specifications; provide separate quotes for calibration with and without adjustment.

Section 2: Multi-sensor node performance specifications (for reference)

The equipment to be calibrated is a custom multi-sensor node, manufactured by Temco Controls, incorporating the sensors described in Table B2. The Temco Controls [Air Lab & PM2.5 Particle Sensor](#) serves as the hardware platform for the custom multi-sensor node.

Access to sensor datasheets and user manuals can be provided separately upon request. Notably, rated performance pertains to sensors prior to node integration (i.e., design-in). The integrated node measures approximately 6 inches tall, 3 inches wide, and 1 inch deep (see Figure #environmentcals-esn). The external probe is for the SCD30.

Additional features:

- Light sensor, no specs available, not to be calibrated
- External microphone potentially included in some nodes, not to be calibrated
- Wi-Fi connectivity
- LCD display may remain on at all times for calibration procedures, or may be configured to automatically turn off after a certain period of time
- Mean Well GSM12U power supply, 120 VAC input with cord 1.8 meter in length

Section 3: Multi-sensor node connectivity, software, and adjustment instructions (for reference)

Instructions:

1. To get the nodes onto your WiFi network, use the [Android-only software](#). Instructions for the Android-based WiFi setup can be found in the [Brochure](#).
2. Use the [T3000 Windows software](#) to connect to the nodes from your computer over the network, and implement adjustment by applying correction in the [T3000 Windows software](#). Instructions for entering calibration factors via the T3000 Windows software can be found in the [software manual](#).

Table B1. Measurement of dry-bulb temperature and relative humidity at 1.0 atm

Calibration point	Dry-bulb temperature (°C)	Relative humidity (%)
A. B. C.	5 25 45	30
D. E. F.	5 25 45	60
G. H. I.	5 25 45	90

Table B2. Sensors incorporated in multi-sensor node

Sensor make/model	Measured quantity	Specs stated on datasheet	Notes
Sensirion SCD30 CO2 and RH/T Sensor Module	Dry-bulb temperature	Measurement range Accuracy Repeatability Response time Accuracy drift	
	Relative humidity	Measurement range Accuracy Repeatability Response time Accuracy drift	
	CO ₂	(see datasheet)	Diffusion-based (no pump)
Sensirion SGP30 Multi-Pixel Gas Sensor	TVOC	(see datasheet)	Used in all 10 nodes Automatic humidity compensation
Ion Science PPB MiniPID 2 #MP3SBLBBU2 photoionization detection (PID) sensor	TVOC	(see datasheet)	Used in 2 of 10 nodes Apparently doesn't need/use humidity compensation
Sensirion SPS30 Particulate Matter Sensor	PM _{2.5}	(see datasheet)	

References

- A2LA (2019). G118: Guidance for Defining the Scope of Accreditation for Calibration Laboratories, Publication Date: 10/09/19. Frederick, MD, American Association for Laboratory Accreditation.
- A2LA (2020). P112 - Policy on Flexible Scopes, Publication Date: 02/25/20. Frederick, MD, American Association for Laboratory Accreditation.
- ANAB (2019). PR 2351, Administrative Process Rule: Preparing a Draft Scope of Accreditation for ISO/IEC 17025 Calibration Laboratories. Milwaukee, WI, ANSI-ASQ National Accreditation Board.
- Alphasense (2014). Alphasense Application Note AAN 201-06, NDIR: Gas Concentration Calculation Overview. Great Notley, UK, Alphasense.
- Andersson, K., Bakke, J.V., Bjorseth, O., Bornehag, C.-G., Clausen, G., Hongso, J.K., Kjellman, M., Kjaergaard, S., Levy, F., Molhave, L., Skerfving, S., Sundell, J., 1997. TVOC and Health in Non-industrial Indoor Environments. Report from a Nordic Scientific Consensus Meeting at Langholmen in Stockholm, 1996. Indoor Air 7, 78–91. <https://doi.org/10.1111/j.1600-0668.1997.t01-2-00002.x>
- ASHRAE (2019). ANSI/ASHRAE Standard 62.1-2019, Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Available at: <https://www.ashrae.org/technical-resources/standards-and-guidelines/read-only-versions-of-ashrae-standards> (Accessed: 3 July 2020)
- BIPM (2008). JCGM 200:2008, International vocabulary of metrology — Basic and general concepts and associated terms (VIM) Paris, France, International Bureau of Weights and Measures.
- Castell, N., Dauge, F.R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., Broday, D., Bartonova, A., 2017. Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? Environment International 99, 293–302. <https://doi.org/10.1016/j.envint.2016.12.007>
- EPA (2011). [Reference and Equivalent Method Applications, Guidelines for Applicants, Revised September 27, 2011](#). Research Triangle Park, NC, U.S. Environmental Protection Agency.
- EPA (2017). [List of Designated Reference and Equivalent Methods, Issue Date: June 16, 2017](#). Research Triangle Park, NC, U.S. Environmental Protection Agency.
- EPA (2020). Particulate Matter (PM) Standards - Table of Historical PM NAAQS [Online]. Available at: https://www3.epa.gov/ttn/naaqs/standards/pm/s_pm_history.html (Accessed: 3 July 2020)
- Forbes, P., 2019. Atmospheric Chemistry Analysis: A Review. Analytical Chemistry 92, 455–472. <https://doi.org/10.1021/acs.analchem.9b04623>
- Goletto, V., Mialon, G., Faivre, T., Wang, Y., Lesieur, I., Petigny, N., Vijapurapu, S., 2020. Formaldehyde and Total VOC (TVOC) Commercial Low-Cost Monitoring Devices: From an Evaluation in Controlled Conditions to a Use Case Application in a Real Building. Chemosensors 8, 8. <https://doi.org/10.3390/chemosensors8010008>
- Han, J., Liu, X., Chen, D., Jiang, M., 2020. Influence of relative humidity on real-time measurements of particulate matter concentration via light scattering. Journal of Aerosol Science 139, 105462. <https://doi.org/10.1016/j.jaerosci.2019.105462>

Hayat, H., Griffiths, T., Brennan, D., Lewis, R.P., Barclay, M., Weirman, C., Philip, B., Searle, J.R., 2019. The State-of-the-Art of Sensors and Environmental Monitoring Technologies in Buildings. *Sensors* 19, 3648. <https://doi.org/10.3390/s19173648>

IAF-ILAC (2017). ISO/IEC 17011:2017 Transition Plan. 29 October 2017, International Laboratory Accreditation Cooperation.

IAS (2019). IAS/CL/022, IAS Guide for Representing Scopes of Accreditation for Calibration Laboratories. Brea, CA, International Accreditation Service.

IEC (2017). ISO/IEC 17025:2017, General requirements for the competence of testing and calibration laboratories. Geneva, Switzerland, International Electrotechnical Commission.

ILAC (2010). ILAC-G18:04/2010, Guideline for the Formulation of Scopes of Accreditation for Laboratories. Silverwater, Australia, International Laboratory Accreditation Cooperation.

ILAC (2013). ILAC-P14:01/2013, ILAC Policy for Uncertainty in Calibration. Silverwater, Australia, International Laboratory Accreditation Cooperation.

ILAC-ISO (2017). Joint ILAC-ISO Communiqué on the recognition of ISO/IEC 17025 during a Three-Year Transition. November 2017, International Laboratory Accreditation Cooperation.

ILAC-OIML (2007). ILAC-G24 / OIML D 10, Edition 2007, Guidelines for the determination of calibration intervals of measuring instruments. Silverwater, Australia, International Laboratory Accreditation Cooperation.

ISO (1994). ISO 5725-1:1994(en), [Accuracy \(trueness and precision\) of measurement methods and results — Part 1: General principles and definitions](#). Geneva, Switzerland, International Organization for Standardization.

ISO (2014). ISO 16000-29:2014(en), [Indoor air — Part 29: Test methods for VOC detectors](#). Geneva, Switzerland, International Organization for Standardization.

ISO (2018). ISO 21501-4:2018(en), [Determination of particle size distribution — Single particle light interaction methods — Part 4: Light scattering airborne particle counter for clean spaces](#). Geneva, Switzerland, International Organization for Standardization.

Jovašević-Stojanović, M., Bartonova, A., Topalović, D., Lazović, I., Pokrić, B., Ristovski, Z., 2015. On the use of small and cheaper sensors and devices for indicative citizen-based monitoring of respirable particulate matter. *Environmental Pollution* 206, 696–704. <https://doi.org/10.1016/j.envpol.2015.08.035>

Karagulian, F., Barbiere, M., Kotsev, A., Spinelle, L., Gerboles, M., Lagler, F., Redon, N., Crunaire, S., Borowiak, A., 2019. Review of the Performance of Low-Cost Sensors for Air Quality Monitoring. *Atmosphere* 10, 506. <https://doi.org/10.3390/atmos10090506>

Kim, J., Shusterman, A.A., Lieschke, K.J., Newman, C., Cohen, R.C., 2018. The BErkeley Atmospheric CO₂ Observation Network: field calibration and evaluation of low-cost air quality sensors. *Atmospheric Measurement Techniques* 11, 1937–1946. <https://doi.org/10.5194/amt-11-1937-2018>

LBNL (2020). Introduction to VOCS and Health [Online]. Available at: <https://iaqscience.lbl.gov/voc-intro> (Accessed: 3 July 2020)

Maag, B., Zhou, Z., Thiele, L., 2018. A Survey on Sensor Calibration in Air Pollution Monitoring Deployments. *IEEE Internet of Things Journal* 5, 4857–4870. <https://doi.org/10.1109/jiot.2018.2853660>

- Mannshardt, E., Benedict, K., Jenkins, S., Keating, M., Mintz, D., Stone, S., Wayland, R., 2017. Analysis of short-term ozone and PM_{2.5} measurements: Characteristics and relationships for air sensor messaging. *Journal of the Air & Waste Management Association* 67, 462–474. <https://doi.org/10.1080/10962247.2016.1251995>
- Mizukoshi, A., Kumagai, K., Yamamoto, N., Noguchi, M., Yoshiuchi, K., Kumano, H., Yanagisawa, Y., 2010. A Novel Methodology to Evaluate Health Impacts Caused by VOC Exposures Using Real-Time VOC and Holter Monitors. *International Journal of Environmental Research and Public Health* 7, 4127–4138. <https://doi.org/10.3390/ijerph7124127>
- NCSLI (2010). Recommended Practice - 1 (RP-1) 2010, Establishment and Adjustment of Calibration Intervals. Boulder, CO, National Conference of Standards Laboratories (NCSL) International.
- NEMA (2016). ANSI C12.1-2014, [American National Standard for Electric Meters—Code for Electricity Metering](#). Rosslyn, National Electrical Manufacturers Association.
- NIOSH (2015). Indoor Environmental Quality [Online]. Available at: <https://www.cdc.gov/niosh/topics/indoorenv/hvac.html> (Accessed: 16 March 2020)
- Omidvarborna, H., Kumar, P., Tiwari, A., 2020. “Envilution™” chamber for performance evaluation of low-cost sensors. *Atmospheric Environment* 223, 117264. <https://doi.org/10.1016/j.atmosenv.2020.117264>
- OSHA (2013). Docket OSHA-2010-0034, Occupational Exposure to Respirable Crystalline Silica -- Review of Health Effects Literature and Preliminary Quantitative Risk Assessment, Occupational Safety and Health Administration.
- OSHA (2020). OSHA Technical Manual (OTM) [Online]. Available at: <https://www.osha.gov/dts/osta/otm/index.html> (Accessed: 6 July 2020)
- Papapostolou, V., Zhang, H., Feenstra, B.J., Polidori, A., 2017. Development of an environmental chamber for evaluating the performance of low-cost air quality sensors under controlled conditions. *Atmospheric Environment* 171, 82–90. <https://doi.org/10.1016/j.atmosenv.2017.10.003>
- PJLA (2017). PL-4, Calibration Scopes of Accreditation. Troy, MI, Perry Johnson Laboratory Accreditation.
- RAE Systems (2013). The PID Handbook, Theory and Applications of Direct-Reading Photoionization Detectors, Third Edition. San Jose, CA, RAE Systems.
- Sayahi, T., Kaufman, D., Becnel, T., Kaur, K., Butterfield, A.E., Collingwood, S., Zhang, Y., Gaillardon, P.-E., Kelly, K.E., 2019. Development of a calibration chamber to evaluate the performance of low-cost particulate matter sensors. *Environmental Pollution* 255, 113131. <https://doi.org/10.1016/j.envpol.2019.113131>
- Sensirion (2018). Field calibration for SCD30 CO₂, humidity, and temperature sensor (Confidential D2 - Version 0.2 – September 2018).
- Spinelle, L., Gerboles, M., Villani, M.G., Aleixandre, M., Bonavitacola, F., 2017. Field calibration of a cluster of low-cost commercially available sensors for air quality monitoring. Part B: NO, CO and CO₂. *Sensors and Actuators B: Chemical* 238, 706–715. <https://doi.org/10.1016/j.snb.2016.07.036>
- Spinelle, L., Gerboles, M., Kok, G., Persijn, S., Sauerwald, T., 2017. Review of Portable and Low-Cost Sensors for the Ambient Air Monitoring of Benzene and Other Volatile Organic Compounds. *Sensors* 17, 1520. <https://doi.org/10.3390/s17071520>

Szulczyński, B., Gębicki, J., 2017. Currently Commercially Available Chemical Sensors Employed for Detection of Volatile Organic Compounds in Outdoor and Indoor Air. *Environments* 4, 21. <https://doi.org/10.3390/environments4010021>

Tryner, J., L'Orange, C., Mehaffy, J., Miller-Lionberg, D., Hofstetter, J.C., Wilson, A., Volckens, J., 2020. Laboratory evaluation of low-cost PurpleAir PM monitors and in-field correction using co-located portable filter samplers. *Atmospheric Environment* 220, 117067. <https://doi.org/10.1016/j.atmosenv.2019.117067>

Tuenge, J.R., Poplawski, M.E., 2020. Specifying Calibration of Energy-Measuring Equipment. U.S. Department of Energy (DOE). <https://doi.org/10.2172/1616176>

Wang, Z., Delp, W.W., Singer, B.C., 2020. Performance of low-cost indoor air quality monitors for PM_{2.5} and PM₁₀ from residential sources. *Building and Environment* 171, 106654. <https://doi.org/10.1016/j.buildenv.2020.106654>

WELL (2020). WELL Building Standard [Online]. Available at: <https://standard.wellcertified.com/features> (Accessed: 6 July 2020)

WHO (2010). WHO guidelines for indoor air quality: selected pollutants. Copenhagen, Denmark, World Health Organization Regional Office for Europe.

Williams, R., Vasu Kilaru, E. Snyder, A. Kaufman, T. Dye, A. Rutter, A. Russell, and H. Hafner. [Air Sensor Guidebook](#). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/159 (NTIS PB2015-100610), 2014.

Williams, R., Kaufman, A., Garvey, S. (2015). EPA/600/R-15/122, [Next Generation Air Monitoring \(NGAM\) VOC Sensor Evaluation Report](#). Washington, DC, U.S. Environmental Protection Agency.

Williams, R., D. Nash, G. Hagler, K. Benedict, I. MacGregor, B. Seay, M. Lawrence, and T. Dye. [Peer Review and Supporting Literature Review of Air Sensor Technology Performance Targets](#). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-18/324, 2018.

(This page intentionally left blank)

