Document containing recommendations or guidelines for low-cost sensors validation

Technical support on air quality to Latin America and the Caribbean countries

Prepared by the Clean Air Institute at the request of the United Nations Environment Programme

October, 2022

Contents

Introduction

Since the beginning of the XXI century, a new type of equipment that seems to offer many advantages in the air quality field has started to gain popularity. These instruments are known as Low Cost Sensors (LCSs) and allow the users to detect pollutant concentrations in ambient air. Compared to the instruments used in regulatory monitoring of criteria pollutants, LCSs have lower costs of purchase, lower energy consumption and are light-weight and small, which makes them easy to transport. Additionally, they are relatively easy to operate and some have developed user friendly applications that can visually display the data, which makes them very attractive for civil society users.

LCSs have been used for diverse objectives. From educational purposes and as teaching tools (allowing communities to get an estimation of their local air quality), to the identification of hotspots, used on personal exposure applications and also on research. LCSs have allowed to raise awareness and highlight the importance of air quality for many communities. They have also been used to increase the density of existing air quality networks. By positioning LCS nearby Reference Grade Monitors, LCSs have provided supplemental data and closed information gaps or supported the identification of local air pollution variation, mainly in cities which already had good air quality monitoring networks and where a considerable number of LCS were deployed.

Unlike Reference Grade Monitors, which use standardized reference methods for each specific pollutant and are accredited under rigorous performance certification processes that guarantee the high quality of the data reported, LCSs lack the reliability of the measured data, mainly because they are very sensitive to environmental factors. Additionally, there are currently no standard testing protocols for the whole range of pollutants measured by current LCS technology. Nevertheless in 2021, the United States Environmental Protection Agency (US EPA) published the first testing protocols, metrics and targets to evaluate the performance of ozone (O_3) and fine particulate matter ($PM_{2.5}$) LCSs for ambient, outdoor, fixed-site non-regulatory supplemental and informational monitoring (NSIM) applications. These reports are key for developing countries that, due to budgetary constraints, might be considering the use of LCS as a supporting tool to acquire information on air quality data for those types of applications.

Based on the reports by the US EPA and on current scientific knowledge, the objective of this document is to provide recommendations and guidelines for countries to develop and implement protocols to test and validate LCS performance, including acceptability criteria.

Current Use of Low Cost Sensors: Application Areas

There are several application areas for the use of the LCS technology. Some have been applied for some time, while others are currently emerging. For instance, government and planning bodies have started using LCS data and combining it with the information provided by well-established reference grade monitoring networks. This has allowed them to acquire a finer scale of air pollution concentrations, to identify hotspots and to support air quality management through targeted policy action.

Another application area are citizen science activities, where local communities get organized to make observations of air pollution parameters. This application area supports educational activities that raise public engagement and awareness by developing public information through the deployment of LCSs for community monitoring. Normally these initiatives occur through a close collaboration amongst citizens, businesses, researchers, NGOs and local governments and institutions.

Another area with several ongoing efforts in the air quality and health community is the collection of data on personal exposure to air pollution. Portable LCSs can provide a sense of the order of magnitude or add exposure measurements to be compared with official data for the personal exposure of populations in specific areas. The LCS technology allows for higher time resolution measurements and more representative data than traditional passive sampling technologies.

Other application areas that are beginning to play a role include basic and applied research by universities research organizations or institutes to acquire short- and long-term data for evaluating pollution spatial variability and for model or emissions validation. Meteorological agencies, government institutions and research institutes and organizations are also starting to benefit from the use of LCS technology, by exploring their use to identify trends on the behavior of atmospheric composition parameters to support international conventions or activities such as the United Nations Framework Convention on Climate Change (UNFCCC), the Global Atmosphere Watch (GAW) Programme of the World Meteorological Organization (WMO) and the Global Climate Observing System (GCOS).

Success Cases in the Use of LCSs

LCSs have been successfully deployed in several projects around the world and there are many success stories of their use. One example is Breathe London, a project that is run by the Environmental Research Group at Imperial College London. The project has a network of 100 LCSs located across greater London that have been installed on lamp posts and buildings. Additionally, it uses mobile LCSs mounted on Google Street View cars to measure air pollution on roadways and has also deployed wearable LCSs on schoolchildren's and teacher's backpacks during a pilot study by the Greater London Authority. The objective of the initiative is to generate data that helps to identify critical pollution areas and benefits of implemented actions in order to improve air quality.

Breathe London offers LCSs to anyone interested and shares the data on a platform based on Google Cloud, which provides user friendly graphs and visualizations. The data obtained is continuously transmitted and published on the Breathe London website, which provides live information of NO_2 and $PM_{2.5}$ concentrations and forecasts of air quality for the upcoming three days. The data produced is used

in combination with the data from the London Air Reference Network, filling its gaps and covering sensitive locations of priority such as primary schools and medical facilities. Locations include a mix of traffic levels and varying distances from major roads and intersections, parks, residential areas, high-traffic streets and other commercial areas. The locations are also defined so that the information they provide can support assessments of the impact of new policies designed to reduce air pollution, such as the Ultra-Low Emission Zone (ULEZ), the Expanded ULEZ and the Low-Emission Bus Zones (LEBZ).

In order to display information in near-real time, the data shown on the website prior to completion of the project is provisional and subject to change as it undergoes additional quality assurance checks. The platform stores data and calibration factors separately and supports the QA/QC process by allowing the technical team to modify calibrations and redact suspect data. The project reserves 3 of the LCSs for performance evaluation over the long-term using periodic collocation studies alongside reference instruments[1].

Another example is the Citizen Scientists program, an initiative in Colombia managed by the Early Alert System of Medellin and the Aburra Valley (SIATA by its acronym in Spanish) of Medellin's local environmental authority, the Metropolitan Area of the Aburra Valley (AMVA) and the Mayor's Office. The project was launched in 2015 when citizens voluntarily offered their homes and workplaces to install a LCS developed by SIATA, to measure air pollution across the Aburra Valley. The LCS are contained in an enclosure that resembles a cloud, which is part of their communications strategy to attract citizens to participate in hosting and taking care of a cloud. SIATA focuses on risk management and it aims to raise education levels and social appropriation of knowledge for different targeted groups, with emphasis on children and youngsters. The Citizen Scientists' network has 250 cloud points that supplement AMVA's reference grade air monitoring system increasing the geographical and social resolution of the existing air quality information.

The LCS network measures PM_{10}, $PM_{2.5}$, temperature and relative humidity and the data is provided in real time on the SIATA website. The project also has an app in both IOS and Android versions where the data can be viewed in user friendly visualizations. Each cloud has two PM sensors inside, so the measurement is redundant. The two sensors are connected to a Raspberry Pi device that sends the information to the SIATA servers using the Wi-Fi network owned by the citizen[2]. The number of citizens to be selected to become Citizen Scientists depends on the resources available at the time from the environmental authority and the sponsors. The project has improved the participants' understanding of meteorological, technological and scientific issues. It has also empowered NGO's and individuals by building citizen's ownership and knowledge of air pollution and solutions while enabling the environmental authorities to track the distribution of PM_{10} and $PM_{2.5}$ across the metropolitan region, for both critical episodes and day-to-day levels, as well as to provide inputs for scientific research and technology development.

There are several additional examples of LCS networks that are currently successfully operating around the world. For instance, the Purple Air network offers LCSs to citizens, schools or other institutions to measure PM_1, $PM_{2.5}$, and PM_{10} and is one of the densest LCS networks in the world. The data reported by the devices is available on their website on interactive maps. Another example which also provides online

---

[1] CEC, 2020.

[2] Ibid.

maps of their data is the Sensor.Community. The network is a contributor driven platform which started in Stuttgart and currently has more than 13,000 devices in more than 75 countries.

The use of LCSs is making possible a paradigm shift in air quality monitoring, where hybrid networks of reference-grade analyzers alongside citizen and community-led monitoring are closing information gaps in monitoring networks as well as raising awareness on air quality issues and actively involving citizen groups in local discussions. Breathe London and the Citizen Scientists Network are successful examples of the use of LCSs for these objectives.

Data Use and Communicating LCS Data

Even as LCSs have proven very useful for applications where they close informational gaps, increase community awareness of air quality problems, among other uses, they are not capable of replacing Reference Grade Monitors and cannot be used for regulatory monitoring due to the quality of the data they report. LCSs have uncertainties that can act as a potential barrier for effective decision making[3]. Therefore, it is important that users understand the limitations of LCSs and of the information they provide. It is recommended to always include the limitations and uncertainties of the reported data and sharing details on how the data is collected, processed and if there are quality assurance processes in place. The objective is to provide information to the public on how the data can be used and interpreted, so that there is transparency for potential new users and to build trust around this new technology.

Low Cost Sensor Technical Considerations and Performance Characteristics

LCSs present several challenges regarding their performance and the quality of the data obtained. Both LCSs that detect gases and particles have limitations, not only due to their sensitivity to environmental conditions, but also because of their particular operational characteristics or even due to mishandling by the user. Below is a quick overview on several aspects that affect the response of LCSs.

Technical Considerations

Before looking into the technical aspects of how LCSs work, it is important to clarify the terminology that is commonly used to refer to LCSs and their components, in order to advance into a homologation of the terminology used. This document will follow the definitions of the World Meteorological Organization as follows: A sensor refers to the basic subcomponent technology that actually makes the analytical measurement of an air pollutant or meteorological parameters such as temperature or humidity. In the case of pollutant sensors, the presence of a gas or particle is normally converted into an electrical signal that can be related to the atmospheric concentration according to the relative magnitude of the signal. A sensor needs additional subcomponents to be deployed (such as power and a processor). An additional term used in the literature is sensor system (also referred to as IOT air quality sensor, environmental sensor, LCS, air sensor) which is a device that integrates one or more subcomponents and other

---

[3] deSouza, P., et.al., 2022.

supporting components that comprise an autonomous detection system. A sensor system can include components that reside remotely from the physical sensor, such as remote data transfer and data processing steps[4]. This document uses the term LCS to refer to a sensor system.

For the case of low cost particulate matter (PM) sensors, most of them use optical measurement techniques. The measurements yielded by an optical sensor can vary compared to methods that measure mass concentrations directly (i.e., gravimetric sampling, which is the gold standard used in Reference Grade Monitors[5]). Optical sensors detect the light scattering signal and convert that information into particle number and mass to estimate concentrations. This method is very common in LCSs because it has a shorter response time and lower power requirements. But particle characteristics can be very variable in field measurements and that introduces a potential error in measurements. Additionally the aerosol's particle size distribution, shape, refracting index, hygroscopicity, volatility, density and other chemical and physical parameters can influence the light scattering process. These parameters are very variable in microenvironments with diverse PM sources and can modify the mass concentrations reported by LCSs[6,7]. That is why calibrations under field conditions are crucial, even if the manufacturer of the sensor provides factory-supplied calibrations.

Another intrinsic characteristic of a sensor is its wavelength. The wavelength of the laser light in the sensor is important, because it determines the particle diameters that the device is capable of detecting. LCSs tend to underperform in low pollution settings[8] because generally their sensors are not capable of detecting particle diameters in the vicinity of (and below) 0.3 μm. Nevertheless particles below that range are of interest in air quality data collection, which is a disadvantage for LCS technology.

LCSs that measure gases also have their own challenges. Electrochemical or metal oxide sensors may have interferences with gases other than the target pollutant and they also are affected by temperature and humidity. Additionally gas sensors gradually lose reactivity and have to be replaced relatively fast, most commonly after one year. Manufacturers of gas LCSs provide both a suggested shelf life (i.e., the time between manufacturing and initial operation) and an operation life span (i.e., the time range from when it is first deployed to the moment when it will no longer be fit for the purpose). Shelf life can typically be around six months when stored under ideal conditions. Some sensors are only usable for one to two years. These combined times are referred to as sensor aging. LCS aging can range from six months to three years. Aging is also a challenge for PM sensors and it happens even if it is not being used. Furthermore, sensors exposed to high smoke concentrations may fail faster[9].

An additional source of error on LCS data can be introduced by the user and occurs when it is deployed for objectives not included in the manufacturer's specifications (e.g., when a user deploys an indoor LCS

---

[4] WMO, 2021.

[5] The term Reference Grade Monitor will be used in this document to denote instruments that use reference methods or equivalent methods that comply with standards and performance certification processes for air quality data collection, normally used for regulatory monitoring purposes. The US EPA refers to these type of certified instruments as Federal Reference Method and Federal Equivalent Method (FRM/FEM).

[6] deSouza, P., et al., 2022.

[7] Raheja, G., et al., 2022.

[8] Liang, L., 2021.

[9] Holder, A., et.al., 2022.

for outdoor measurements or for mobile instead of stationary data collection). Therefore it is important to adhere to the manufacturer's specifications. As a clarification, the recommendations on this document mainly focus on outdoor fixed site applications, unless otherwise explicitly stated.

In terms of environmental conditions that affect LCS's performance, a factor that influences particle size is relative humidity. When particles are not desiccated by the instrument prior to mass estimation, relative humidity can cause hygroscopic particle growth, which can yield a mass overestimation[10]. As mentioned above, optical LCSs do not have capabilities to desiccate particles. Moreover, relative humidity can also affect the refractive index of particles via water moistening, therefore LCS data should be carefully handled when relative humidity is above 75%[11]. Extreme temperatures (either low or high) can also affect LCS response. Finally not all LCS are weatherproof. In those cases the user needs to provide an enclosure to protect the device from weather conditions.

In summary, LCS technology is very sensitive to a variety of parameters and conditions that affect their response and measurement reporting, therefore the data obtained from LCSs needs to be treated with precaution.

Performance Related Characteristics: Definitions and Relevance

There are several performance related characteristics of LCSs that can have an effect on the quality of the data collected. These performance related characteristics can be used to establish values for acceptability criteria in order to evaluate the performance of a LCS. As first steps to a successful LCS deployment, it is important to understand (a) what those criteria are, (b) why they are relevant and how they may impact the collected data, (c) how they are influenced by sensor and/or environmental factors, and (d) what the approach is to correct potential data divergences. These performance characteristics for LCSs are presented below:

❖ **Precision:** refers to the ability of the sensor to consistently measure the same concentration multiple times under identical conditions. Random or unknown errors can introduce scatter into the data, and that is what precision describes. Precision is commonly expressed as a standard deviation, but the coefficient of variation is also used.

Data precision increases as more frequent data is collected over a period of time. Precision can be improved by averaging raw data together. This is because grouping data into averages allows random errors to cancel each other out, making the resulting averaged data more precise (provided that the measurements are unbiased – see Bias below). Data from multiple sensors at the same location can also be grouped and averaged to increase the precision of the combined measurement. It is important to consider the time periods which you need your data to be analyzed over when grouping data. The user should also consider that grouping data can result in fewer individual data points.

---

[10] deSouza, P., et al., 2022.
[11] Liang, L., 2021.

The manufacturer of a LCS will have information about reported precision for it. Nevertheless it is important for users to perform their own precision measurements to increase the quality of the data that the specific LCS is collecting. To determine precision, (i.e., to determine how the specific LCS behaves and replicates measurements and/or how it deviates from them), the LCS can be tested for the zero and for a known concentration. In order to do this the user can expose the LCS repeatedly to air with no pollutant and then again multiple times to a known concentration of the target pollutant. This will allow to identify the precision of the sensor.

❖ **Bias:** this term refers to a persistent error in the LCS's reported concentration, which might be lower or higher than the real concentration of the pollutant of interest. This type of error is repeatable therefore, it can be identified by taking multiple measurements and comparing those with the measurements taken by a Reference Grade Monitor (which should be located in close proximity to the LCS). The bias will be a constant value that will need to be added or subtracted from the collected data to obtain the real concentration (i.e., the concentration measured by the Reference Grade Monitor).

Bias can be caused by the LCS itself, by a problem with the overall measurement method or by a human error by the LCS's operator, who might be making a persistent mistake for every measurement[12]. Bias can change over time as well, due to environmental conditions like temperature and humidity, by the lifespan of the LCS or by interference from other chemicals present in the atmosphere (see also Drift).

As with precision, the manufacturer of a LCS will have information about reported bias, but it is important for the user to perform their own bias measurements to increase the quality of the data that the LCS is collecting. To correct for bias, it is important to perform calibrations frequently and to compare the LCS with Reference Grade Monitors and/or with other LCSs, even with ones that work with a different measuring principle. Altering the method or correcting operational procedures are also alternatives to correct for bias, when the causes are a problem with the measurement method or human error respectively.

❖ **Linearity**: this term defines to what extent a LCS's measurements can relate to those reported by a Reference Grade Monitor. This is of importance for the calibration process of the LCS, where the user will look for the regression model that can best describe the relationship between both instruments, to further use it to correct the data to be collected. Linearity is commonly determined using the coefficient of determination R^2.

An important consideration is that R^2 can be misleading if the objectives of the project target concentrations close to the detection limit of the LCS (see Detection Limit). A recommended option for that case would be to use the Root Mean Square Error (RMSE) instead[13].

---

[12] US EPA, 2014.
[13] deSouza, P., et al., 2022.

❖ **Detection Limit:** refers to the lowest concentration above zero that the sensor is able to measure at a stated level of certainty. The Method Detection Limit (MDL) is often used and is defined as 99% confidence that the measurement is not instrument noise[14].

The manufacturer of a LCS can provide the detection limit for a LCS. If the particular objective of the data collection is to measure at the low end of the concentration range of the pollutant of interest, it is very important to measure the detection limit often, because it may vary over time. A calibration gas can be used, by diluting it until the LCS cannot reliably measure it anymore. Another useful option is to compare the LCS measurements with those of a Reference Grade Monitor that is measuring low background concentrations.

However, the US EPA does not recommend to include the detection limit as a performance metric and has not determined testing protocols for the detection limit for LCSs, because they have not identified a methodology for measuring the detection limit which can yield consistent and reproducible results for a variety of LCSs.

Other factors make the interpretation of a detection limit challenging. In the case of O_3, "some sensors do not provide true measurements for zero air making those measurements more difficult to interpret in the context of the detection limit. Most manufacturers typically list the range of values a device can measure as being zero to some positive value (e.g., 0 – 50 ppbv)"[15]. As for fine particulate matter ($PM_{2.5}$), LCS do not report negative concentrations and as with O_3, they report zero for low concentrations. "Additionally, a sensor's response to low concentrations may have a different slope and/or variable uncertainty across the low concentration regime (0 - 8 $\mu g/m^3$)"[16].

Nevertheless, since the detection limit is a characteristic that will define if the measurement needs for a specific case can or cannot be met by a specific LCS, these information has been included here for consideration in each particular case. The US EPA recommends to report the detection limits provided by the manufacturer.

❖ **Drift:** refers to a gradual change (either an increase or a decrease) in the LCS's response over time. Drift shows a decreasing or increasing trend in the data over time, but does not reflect a real change in the environmental concentrations. Drift can gradually affect accuracy, precision and increase bias as well.

Drift can be caused by a variety of factors including weather conditions (such as exposure to humid air or to warm temperatures), LCS poisoning or internal characteristics of the LCS, such as the loss of strength or efficiency of the light source (for the case of optical sensors).

Drift can be addressed by calibrating the LCS frequently, so that it only drifts a small amount between recalibrations. The frequency of calibration will depend on how much drift occurs.

---

[14] US EPA, 2014.
[15] US EPA, 2021.
[16] US EPA, 2021.

❖ **Error**: this term measures the disagreement between the pollutant concentrations reported by the LCS and the Reference Grade Monitor. Error can be determined using the root mean square error (RMSE) and the normalized root mean square error (NRMSE).

Other relevant characteristics of LCSs

❖ **Data Completeness:** refers to the amount of valid data that was obtained vs the amount that was expected, and is expressed as a percentage. Incomplete data sets can interfere with the analysis of the information obtained because of the gaps generated, which hinder the ability to maintain data continuity and to obtain representative high-quality data. Gaps of information may be caused by data transmission problems due to low reliability of a wireless connection (in the case that data is transmitted wirelessly), or to loss of power (in which case additional data will be lost during the time needed to restart the device). The time that an LCS is out of line for repairs and frequent or long calibrations can also impact data completeness.

❖ **Response Time:** this term describes the time a LCS takes to respond to a change in concentration. Depending on the objectives of the project a LCS that responds quickly might be required (e.g., if there is a need to collect data that changes rapidly, such as for mobile applications or for short lived pollutant plumes). For those cases it is recommended to have a response time of less than 1 minute. For the detection of outdoor quality trends that change gradually, detection at tens of minutes may be sufficient[17]. Manufacturers use either t_{90} (for fast response time LCSs) or t_{50} (for LCSs with slower response times). They represent the time taken by the LCS's response to get to either 90% or 50% of the pollutant that is being measured.

❖ **Measurement Duration:** is the length of time over which a measurement is collected. As with the sensor response, a shorter measurement duration will allow to detect rapidly changing concentrations. Measurement duration is dependent on the response time of the LCS, among other factors.

❖ **Measurement Frequency:** this term refers to the number of measurements collected per unit of time. Measurement frequency is dependent on the response time of the LCS.

Selection Criteria

After having a better understanding of how LCSs work and what are key relevant performance characteristics, it is easier to make an informed decision on how to select the sensor or LCS that better adjusts to a user's needs. The user should have previously defined the scope of their project and the guiding questions they want to answer. These aspects will provide information on what the target pollutant is, what will the duration of the data collection be, what the field conditions are, the level of quality of the measurements needed and the type of measurements required (i.e., short term, long term, stationary and/or mobile). Based on that information, the following checklist can be used to assess different LCS options and select the option that is best suited for the project:

---

[17] US EPA, 2014.

✓ Method of Measurement, Detection Range and Detection Limit: What are the target concentrations of the project? Does the LCS have the capability to detect the full range of expected concentrations? What type of measurement is required (short term, long term, stationary and/or mobile)? (See more details under the *Performance Related Characteristics: Definitions and Relevance* section).

✓ Precision and Bias: What are the reported precision and bias by the manufacturer or the literature? What is the application area of the project and what are acceptable target values for precision and bias error? (See more details in Table 12).

✓ Response Time: How quickly does the LCS respond to changing conditions? (See more recommendations under the *Other relevant characteristics of LCSs* section).

✓ Data Storage and Transfer: Is the data stored locally or in in a database maintained by the manufacturer or a third-party company? Is the data stored in an easily readable format?

✓ Data Transparency and Ownership: Does your project need raw data or just final values? Is a license required to access the data? (See more details under the *Data considerations* section).

✓ Ease of Use and installation: Is it easy to setup the device? Will you need to provide training sessions for its use? Does the device come with a weatherproof enclosure?

✓ Commercial availability: Is the LCS a prototype of a product that is not yet available in the market?

✓ Sensor Aging (Lifetime): How long will your project collect data? Will you have to replace the LCSs during the project duration?

✓ Warranty and Product Support from Manufacturer: Does the LCS have a warranty offered by the manufacturer? Do they offer repair or recalibration?

✓ Ease of Maintenance and Maintenance Costs: Is it easy to maintain the device? Maintenance may include replacing filters and/or batteries, cleaning out sensors and internal surfaces using compressed air, troubleshooting network connectivity issues, replacing broken components, and returning malfunctioning monitors to the manufacturer for repair and recalibration[18].

✓ Cost: Are you purchasing just a sensor and need additional subcomponents, or will you acquire a LCS? How many devices do you need?

Regarding the costs, it is important to clarify that when referring to LCSs, the low cost refers to the purchase price of the device and does not include other additional costs that will come up when using the LCS. Consider if you are buying just the sensor and you will need to acquire additional hardware or subcomponents to deploy it (which might require soldering and programming skills). Identify and estimate

---

[18] Tracking California, Comité Civico del Valle, and University of Washington, 2018.

additional costs of installation and operation, design and implementation of a quality assurance and quality control, maintenance costs such as adjustment or periodic repair a well as data storage, management and visualization (and related software). Remember to estimate the costs associated to the personnel needed to support this work. Some LCSs might have additional costs for data access through licenses (see more details under the *Data considerations* section). Finally consider the amount of LCSs you will need (include adding extra devices to replace failed ones), since buying in bulk directly from the manufacturer may be cheaper. A useful resource for cost estimation is the 2021 WMO report, which includes estimates of costs of operation of LCS networks by size[19].

Testing the Performance of a Low Cost Sensor: Protocols

Calibration is key when using LCSs since this process relates the response of the LCS to that of a Reference Grade Monitor through the development of a calibration curve. Calibration models are usually used to adjust for environmental conditions such as temperature, relative humidity, dew point and bias. Due to all of the factors that can affect the measurements reported by a LCS, it is crucial to design a calibration procedure as a quality control (QC) measure. Even as some LCSs may have information on how to calibrate the device or as they can be purchased pre-calibrated, it is critical to perform calibrations under the conditions where the device will be used. Because the environmental conditions vary by region, it is important to develop case-specific models for LCS, instead of using generic or manufacturer-provided general calibration factors[20]. In any case, when purchasing a LCS it is important to know if it has been calibrated by the manufacturer and to include this information in the report of the calibration. LCS manuals may also contain information on how long the calibration will last once the LCS is being used.

Performing periodical calibrations will provide availability of information to produce more accurate data and identify and address changes in the LCS's performance during that time frame. Since the performance of the LCS can vary over time, it is recommended that LCSs are calibrated at least in three different instances: before starting a set of data collections, during and after a set of data collections. Due to the fact that relative humidity and temperature will change when seasons change, a recalibration is also recommended right before a season changes, during the transition between seasons and after the season change[21]. A calibration and re-calibration plan should be prepared, to establish the schedule for recalibration. For the plan, take into consideration potential additional time delays due to administrative procedures for acquiring permits to mount the LCSs adjacent to Reference Grade Monitors.

The time intervals between recalibrations will depend on the LCS being used and the objective of the data collection, so it might be daily, weekly, quarterly, semi-annually or annually. A need for recalibration may also be determined based on deviations in performance metrics identified during the data collection (such as instruments that drift). For instance, some users track the results of the code packages used for the data analysis and establish specific deviation values of concern for the performance metrics used. If several performance metrics reach those values, then a recalibration is launched. If not, the proposed

---

[19] WMO, 2021.
[20] Liang, L., 2021.
[21] Retama, A., 2022.

recalibrations on the plan can be followed[22]. The scheduling should take into consideration the aging of the equipment and replacement of the LCS so that they are not used after their operating lifetime is over.

A calibration checks and adjusts the LCS's response to a known reference value (i.e., to a true concentration of a pollutant). The known reference value used to adjust the LCS reported values can be obtained either using a reference standard or a Reference Grade Monitor. The former exposes the LCS to a widely accepted reference standard and relates the LCS response to the known concentration of the reference standard. The latter compares the LCS response to the response of a Reference Grade Monitor, which by definition, has been calibrated with a recognized standard.

Reference standards can be obtained from science product vendors. For gases, the standards are normally sold in a compressed gas cylinders. Particle standards are powders that need to be resuspended into a clean compressed-air source prior to the measurement. Due to the nature of these standards testers might require a laboratory setting to use them. For instance, O_3 and NO_2 can degrade very fast. O_3 cannot be delivered in a gas cylinder and has to be made by an O_3 generator at the time of the calibration. This device can produce known concentrations of the gas, but is expensive and may not be available for all LCS users. In the case of NO_2, small cylinders have one-year expiration dates, but degrade quickly, as mentioned. Additionally some standards have to be mixed with a clean air source. In the case of particle standards, preparing the particles for measurement requires sophisticated laboratory equipment (e.g., a reference measurement is needed to determine the mass concentration when resuspended; some need a sprayer as well as dilution air or an air diffusion drier). Again, these conditions may be restrictive for LCS users. Therefore, depending on the specific conditions of the data collection, testers might have to consider performing calibration with a reference instrument.

Collocation

When deploying several LCSs, it is necessary to calibrate each and every LCS that is going to be used, because each will have a different response due to their specific individual characteristics. This is true even if the LCSs belong to the same brand and production batch. Each LCS must have its own calibration equation which considers one or several variables.

As mentioned previously, LCS are sensitive to environmental conditions. In order to better understand the accuracy of the data produced by a LCS, calibrations should be performed under the same environmental conditions as the ones under which the desired data will be collected (i.e., ranges of temperature, humidity, concentrations, background air, etc.). Calibrations are normally performed by simultaneously operating LCSs with one or several Reference Grade Monitors. This process is known as collocation. The data sets from the LCS and the Reference Grade Monitors can then be compared, with the objective of adjusting the LCS response.

For some cases, the collocation is performed at the same site where the measurements of the project will be made (i.e., the calibration site is the same as the target measuring site or within the same neighborhood or town). In many other situations, for instance, where the objective of the project is to

---

[22] C. Hoyos, 2022.

collect data in remote areas, a Reference Grade Monitor may not be available at a short distance. Nevertheless research has shown that when some LCS's data sets are corrected for relevant parameters (such as temperature and relative humidity), the output values can be highly accurate when compared to Reference Grade Monitors, mainly for $PM_{2.5}$. This suggests that correction factors are transferable within geographical areas with approximately homogenous climatology as well as particle size, composition and loading[23].

In the case of $PM_{2.5}$, when choosing a collocation site, it is important to find a place that will resemble the pollutant sources, so that it can be assumed that particles will have a similar range of compositions. In those cases, the collocation of the Reference Grade Monitor should be representative of the conditions of the target measurement area.

The collocation will then provide data to develop a calibration equation that can relate the response of the LCS as closely as possible with the measurements of the Reference Grade Monitor. Once a calibration equation is obtained, it can be used on the target location, assuming that sampling conditions are within the same range as those present during the collocation period.

The US EPA has developed two testing protocols that are recommended for LCSs: Base testing and Enhanced Testing. The former is focused on testing on the field, to expose the equipment to environmental conditions and obtain information on the performance of the LCS in a real-world setting. The latter is performed under more controlled conditions, using an exposure chamber in a laboratory, and seeks to evaluate the LCS's response to a wider range of conditions, which might be challenging to easily encounter in the field. It aims to better understand the response of the LCS to interferents, temperature, relative humidity, as well as drift and accuracy at higher concentrations. Enhanced testing provides more comprehensive information on LCS performance since conditions are known and results are repeatable and reproducible.

It is important to highlight that both testing procedures are designed for ambient, outdoor, fixed site, Non-regulatory Supplemental and Informational Monitoring (NSIM) applications. Other settings, such as indoor, personal exposure or mobile monitoring require protocols that are not considered under these two testing alternatives. The recommendation of the US EPA is to perform at least Base testing, as Enhanced testing requirements might not be easy to access.

Data considerations

It is recommended when using LCSs that the measurements are logged internally on each LCS or through a central data acquisition system and to not have the LCS connected to the internet. This is to prevent losing data if the internet connection or network fails. It can also be useful to do so in cases were the LCS will be deployed in remote areas where there is no internet or cellular access. Additionally some LCSs use nearby measurements to verify operation or correct data. In those cases, it would be useful for the user to know how the LCS performs with no access to the network. Lastly, "it is difficult to verify the integrity

---

[23] Raheja, G., et al., 2022. A Network of Field-Calibrated Low-Cost Sensor Measurements of PM2.5 in Lomé, Togo, Over One to Two Years. *ACS Earth and Space Chemistry* 6 (4), 1011-1021. DOI: 10.1021/acsearthspacechem.1c00391

of the data if the LCS is connected to the internet (e.g., firmware could update during testing). Many consumers want the ability to trace and verify how data is transformed from a raw format to a final format. This can be especially problematic for LCSs that rely on machine learning approaches"[24].

Some LCS cannot operate without an internet connection or cannot log in internally. The choice of LCS should be carefully studied under these considerations and depending on the project objectives and target sites. For LCS with cellular or internet connection requirements, this information should be included in the reports and no data from collocated or nearby monitors should be used to manipulate LCS data processing procedure for primary testing and reporting.

In addition, the user should ensure that the data streams from the LCS and the Reference Grade Monitors used are time aligned. This will allow to properly compare the measurements. Remember to check the LCS as well as the Reference Grade Monitors for the target pollutant, for interference pollutants and for temperature and relative humidity. This can be done by using a common data logger. If this is not available, adjust instrument times to a common standard clock and/or check time stamps when devices are started and stopped.

Finally, of importance when data is reported as an average, is to have clarity on whether the average is time ending or time beginning. "For example, when logging hourly averages, the 7:00 time stamp may reflect data collected between 6:01 - 7:00 (time ending) or 7:00 - 7:59 (time beginning)"[25].

A final recommendation in terms of data accessibility is to consider licenses for data visualization and the number of users a license allows. Some LCSs may require a license to access the data collected when it is stored virtually in a cloud system. That may limit the number of users that can have access to the LCS data, which might in turn, become an issue if several institutions or stakeholders are collaborating and need simultaneous access to the collected data. Therefore, before choosing a LCS, always check the data license requirements and determine if the project budget will allow to pay for them.

Base Testing

Base testing should be performed on two (2) field deployments using at least three (3) LCSs from the same make, model and firmware version in order to identify variations amongst identical LCSs. The LCSs should be tested with collocated Reference Grade Monitors (which should be previously calibrated) for a period of at least 30 days per deployment. Temperature and relative humidity calibrated monitors are also needed for base testing.

The testing sites should represent a range of temperatures, relative humidity, concentrations and weather conditions that can give information on how the LCS will be perform under the conditions expected in the area where the data collection will be performed according to the specific objectives of the project. Details of the number of sites to use are provide in Table 1. For PM$_{2.5}$ base testing, if the objectives of the project target high concentrations (e.g., wildfire or smoke), it is recommended to increase the number of test sites and include areas affected by those types of events and higher PM$_{2.5}$ concentrations.

---

[24] US EPA, 2021. p.7.
[25] US EPA, 2021. p.7-8.

Table 1. Base testing considerations for test site selection and setup for PM$_{2.5}$ and O$_3$

Considerations	Fine Particulate Matter (PM$_{2.5}$)	Ozone (O$_3$)
Site Number and Characteristics	Two (2) test sites in different climate regions that provide the greatest possible variety in variables including: • Concentrations • Particle sources • Particle types • Particle size distributions	Either: • One (1) single test site during two (2) different seasons Or • Two (2) different test sites
Test site goal average concentrations for at least one day	≥ 25 µg/m³ (24-hour average)	For one single test site: • ≥ 60 ppbv (1-hour average at an O$_3$ season) • None (1-hour average at a non- O$_3$ season) For two different test sites: • ≥ 60 ppbv (1-hour average at site 1 on an O$_3$ season) • None (1-hour average at site 2 on a non- O$_3$ season)
Data averaging for evaluation of LCS vs Reference Grade Monitor	24-hour averages	1-hour averages
Additional measurements to interpret results (optional)	• Particle size distribution • Particle chemical composition (e.g., carbon, nitrogen) • Refractive index	• CO • NO$_2$ • SO$_2$ (to be performed using calibrated Reference Grade Monitors)
LCS setup	Mounted: • within 20m horizontal of the Reference Grade Monitor • exposed to unrestricted air flow	
LCS location of air sampling inlet	Within a height of ±1m vertically of the air sampling inlet of the Reference Grade Monitor.	
LCS distance from each other	~ 1m apart	
LCS Protection from environmental conditions	As recommended by manufacturer, install within a weather protective shelter/enclosure, without affecting air flow around it.	
Cautions for LCS location	Do not place LCSs: • Near structures/objects that can affect air flow. • Near structures/objects that can block the air intake (e.g., against a wall, near a vent, on the ground blocking the inlet). • Near structures/objects that can alter temperature or relative humidity near the sensor (e.g., vents, exhausts). • Near sources/sinks that can alter pollutant concentrations (e.g., idling cars, smoking). • In locations with risk of vibration, electrical shock, or other potential hazards.	

Adapted (US EPA, 2021).

Table 1 also includes additional measurements that the user may want to include during base testing. The data provided by these measurements will allow the user to understand physical reasons for variations in performance of the LCS for the case of $PM_{2.5}$ and to consider interferences, for the case of O_3. The additional simultaneous measurements collected for O_3 may help verify results for enhanced testing as well.

Regarding the site selection, Table 1 includes target concentrations to be met for at least one day of the 30-day testing period on each testing site. For $PM_{2.5}$ the goal is to select a testing site where a 24-hour average concentration of at least 25 μg/m^3 is detectable, to help ensure that statistics will be comparable through the sites and to prevent obtaining a low R^2 due to low concentration ranges. For the case of O_3, the target concentration is a 1-hour average of at least 60 ppbv. The recommendation takes into consideration the possibility that high O_3 concentrations may occur during the summer season and that for that reason, temperature ranges will be decreased. Consequently, a second test on a different season or at a different site is recommended in order to have a wider range of temperature. This will not only allow to include different meteorological conditions, but the potential to detect a wider range of interfering co-pollutants. An additional recommendation for O_3 is to include testing if there are available locations that have winter O_3 episodes. Historical information on pollutant concentrations and meteorological conditions that can be used for site selection may be available through existing ambient air monitoring networks or local/national authorities.

After selecting a testing site for the base testing protocol, obtain the site ID and information on the calibration or certification date for the monitors used (including Reference Grade Monitors for the target pollutant, for interference pollutants and for temperature and relative humidity). Include a copy of the calibration certificates in your report. If the Reference Grade Monitors for the pollutant, temperature or relative humidity are not set up at the selected testing site, set them up to follow the criteria for the sampling probe inlet or monitoring path in Table 2.

Table 2. Sampling Probes or Monitoring Path Siting Criteria*

Description	Distance (meters)
Height from ground	2 to 15
Horizontal and vertical distance from supporting structures	> 1
Distance from trees	> 10**
Distance from roadways	> 10 to 250†

*US EPA, 2021.

**Should be greater than 20 meters from the tree(s) dripline and must be 10 meters from the dripline when the tree(s) act as an obstruction (see 40 CFR Part 58, Table E-4 of Appendix E).

†The roadway average daily traffic, vehicles per day determines the minimum distance (see 40 CFR Part 58, Table E-1 of Appendix E).

Steps for Base Testing

Below is a step-by-step list for the implementation of base testing. Please refer to the previous sections for detailed information and background on some of the steps below[26]:

---

[26] Adapted from US EPA 2021.

1. Select the required test site according to the criteria listed in Table 1.

2. Record all the information of the Reference Grade Monitoring setup at the selected test sites including:
    a. Calibration or certification dates for all monitors used (including Reference Grade Monitors for the target pollutant, for interference pollutants and for temperature and relative humidity). The calibration of the Reference Grade Monitors should be performed after the LCS is in place at the testing site, not before.
    b. Include a copy of the calibration certificates in your report.
    c. If using an existing ambient air monitoring network, record site ID.

3. Verify that at least three (3) LCSs are used for base testing and that they are from the same make, model and firmware version. Make sure the firmware version is not updated during the testing period. Do not modify any manufacturer's calibration(s) and use them as they were received to obtain data on out-of-box performance.

4. Store data locally on the LCS or on a data logger by disconnecting the LSCs from the internet. If an internet connection is required for the LCS operation, make sure they do not use collocated or nearby measurements to verify operation or correct data during the base testing period.

5. Record the information about equipment and set-up in the base testing report including:
    a. Parameters measured and units (e.g., pollutant(s), temperature, relative humidity, dew point).
    b. Sampling time interval (e.g., 1-minute, 15-minute, 1-hour, 24-hour).
    c. Data storage (e.g., local data card, cloud system).
    d. Data transmission method(s), if applicable (e.g., manufacturer's cloud server).
    e. Form of data stored (e.g., raw data, corrected or clean data).
    f. Data correction approach (if applicable) including:
        i. Procedure used to correct the data including:
            - how the data are corrected (e.g., manufacturer derived multilinear correction),
            - variables used to correct the data (e.g., relative humidity, temperature),
            - where the correction variable(s) come from (e.g., on-board Relative Humidity (RH) sensor), and,
            - how the data are validated or calibrated (e.g., RH sensor is calibrated by the manufacturer).
        ii. If the way data are corrected is static and it does not change, record this information and any mathematical approaches used.
        iii. If the way data are corrected is a dynamic process, record the following:
            - when and why the process changes,
            - how/where changes are recorded and,
            - how the correction method is validated.
    g. Data analysis/data correction scripts (e.g., Jupyter Notebook, R Markdown).

    h. Location of final reported data and its format (e.g., data provided as .csv, website shows raw data and corrected data on user interface, expanded definitions of data headers).

6. Install the LCSs at the selected test site as per the recommendations on Table 1.

7. Take pictures that show the setup of the equipment at each test site and report distances in the base testing report.

8. Verify that the data logging and storage will collect and store all the equipment data in a way that can be accessed later. Verify the storage capacity is enough to prevent older data to be overwritten while allowing the base testing data to be saved.

9. Provide a warm-up and stabilization period for all the equipment (as specified by the manufacturer).

10. Confirm that all the equipment is reporting measurements.

11. Conduct a one-point flow rate verification check (for $PM_{2.5}$), or a one-point QC check (for O_3) on the Reference Grade Monitors and record the date of the check.

12. Allow all equipment to run during the same time period, for at least 30 consecutive days to allow for comparable results.

13. Follow the manufacturer's maintenance recommendations for all equipment throughout base testing. Record and report all maintenance or troubleshooting performed on the instruments including dates and times (e.g., power cycling, Reference Grade Monitor flow rate verification check, Reference Grade Monitor one-point QC check).

14. Record and report the reasons for missing or invalidated data. For the 30 consecutive day base testing at least 75% uptime with all instruments reporting is ideal.
    a. For $PM_{2.5}$, this corresponds to all equipment reporting at least 23 valid 24-hour pairs of time-matched data points over the course of the 30-day deployment.
    b. For O_3, this corresponds to all equipment reporting at least 540 valid 1-hour time-matched data points over the course of the 30-day deployment (720 hours total).
    c. If a LCS fails irreparably before the 30-day deployment is complete, another LCS should not be substituted. In addition, the LCS should not be sent back to the manufacturer for repairs without restarting the testing. A preliminary report could present results with documentation explaining why the LCS failed. Testing can be restarted with three (3) LCS.
    d. Occasionally, low uptime or a deployment period of less than 30 days might occur due to an unplanned event (e.g., an electrical outage or a weather event such as a hurricane or tornado). In those cases, the dates and reasons for missing data should be recorded. In these scenarios, ideally testing would continue/resume until:

      i. At least 540 valid 1-hour pairs of time-matched data points are collected for O_3. If data from any piece of equipment is not available during each 1-hour sampling period, record and report the reason.

      ii. At least 23 valid 24-hour pairs of time-matched data points are collected for $PM_{2.5}$. If data from any piece of equipment is not available during each 24-hour sampling period, record and report the reason.

    e. Additionally, if any data are invalidated due to QC criteria, record the reason and criteria used. Reference Grade Monitors have more established QC criteria. QC criteria for the LCS may be available from the manufacturer or may be developed as part of these tests.

15. Select the next test site for the second field deployment according to the criteria listed in Table 1.

16. Repeat the steps for base testing for the second field deployment using the LCS from the first field deployment, if possible. Generate a separate base test report for the second field deployment.

Enhanced Testing

The purpose of the Enhanced testing protocol is to determine the response of a LCS to environmental conditions due to:
(a) Temperature,
(b) Relative Humidity,
(c) Interferents (if applicable)
(d) Drift (i.e., changes in the response of the LCS with time), and
(e) High concentrations.

Enhanced testing should be performed using at least three (3) LCSs from the same make, model and firmware version in order to identify variations amongst identical LCSs at an exposure chamber that can control environmental conditions. The LCSs should be tested with collocated Reference Grade Monitors (which should be previously calibrated). Temperature and relative humidity calibrated monitors will also be needed for Enhanced testing. The recommended ranges of temperature (T), relative humidity (RH) and concentrations that the exposure chamber should be able to control, maintain and monitor are listed in Table 3. The Enhanced testing report should include chamber specifications, characterization and any laboratory intercomparison.

Table 3. Enhanced testing setup considerations for $PM_{2.5}$ and O_3

Considerations	Fine Particulate Matter (PM₂.₅)	Ozone (O₃)
Exposure chamber ranges	• T: 19 - 41°C • RH: 35 - 90% • $PM_{2.5}$: 5 - 280 µg/m³.	• T: 19 - 41°C • RH: 35 - 90% • O_3: 10 to 140 ppbv • CO: 30 to 40 ppmv • NO_2: 90 to 115 ppbv • SO_2: 65 to 85 ppbv.

Considerations	Fine Particulate Matter (PM$_{2.5}$)	Ozone (O$_3$)
Exposure Chamber Capabilities (General)	• Ability to maintain atmospheric pressure by balancing the incoming flow with the sampling and vent flow. • Allows for air to be well-mixed. • Capable of accommodating 3 or more LCSs. • Sampling ports should not be obstructed and allow for sufficient sampling flow.	
Exposure Chamber Capabilities (Specific)	• Ability to maintain the particle size distribution, composition, and concentration. • Particle generation system should be positioned above the exposure chamber and connected with as few bends as possible to prevent particle loss and build-up before particles enter the chamber. • PM$_{2.5}$ Reference Grade Monitor should be mounted directly below the sampling chamber to reduce particle loss in the sampling line due to bends.	• The nonreactive or passivated tubing connecting the chamber to the Reference Grade Monitors should be short so as not to affect what is sampled. • Contain nonreactive or passivated chamber walls.
Additional measurements to interpret results	• Particle size distribution • Particle chemical composition (e.g., carbon, nitrogen) • Refractive index These are optional additional measurements.	• CO • NO$_2$ • SO$_2$ (to be performed using calibrated Reference Grade Monitors)

Adapted (US EPA, 2021).

Steps for Enhanced Testing

Below is a step-by-step list for the implementation of Enhanced testing. Please refer to the previous sections for detailed information and background on some of the steps below[27]:

1. Check that all the equipment to be used is properly calibrated. Record calibration or certification dates for all the monitors used (including Reference Grade Monitors for the target pollutant, for interference pollutants and for temperature and relative humidity).

2. Include a copy of the calibration certificates in your report.

3. Conduct a one-point flow rate verification check (for PM$_{2.5}$), or a one-point QC check (for O$_3$) on the Reference Grade Monitors and record the date of the check.

---

[27] Adapted from US EPA 2021.

4. Verify that at least three (3) LCSs are used for Enhanced testing and that they are from the same make, model and firmware version. Make sure the firmware version is not updated during the testing period. Do not modify any manufacturer's calibration(s) and use them as they were received. The LCSs can be the same ones used during base testing.

5. Store data locally on the LCS or on a data logger by disconnecting the LSCs from the internet. If an internet connection is required for the LCS operation, make sure they do not use collocated or nearby measurements to verify operation or correct data during the enhanced testing period.

6. Record the information about equipment and set-up in the Enhanced testing report including:
   a. Parameters measured and units (e.g., pollutant(s), temperature, relative humidity, dew point).
   b. Sampling time interval (e.g., 1-minute, 15-minute, 1-hour, 24-hour).
   c. Data storage (e.g., local data card, cloud system).
   d. Data transmission method(s), if applicable (e.g., manufacturer's cloud server).
   e. Form of data stored (e.g., raw data, corrected or clean data).
       i. Procedure used to correct the data including:
          - how the data are corrected (e.g., manufacturer derived multilinear correction),
          - variables used to correct the data (e.g., relative humidity, temperature),
          - where the correction variable(s) come from (e.g., on-board RH sensor) and,
          - how the data are validated or calibrated (e.g., RH sensor is calibrated by the manufacturer).
       ii. If the way data are corrected is static and it does not change, record this information and any mathematical approaches used.
       iii. If the way data are corrected is a dynamic process, record the following:
          - when and why the process changes,
          - how/where changes are recorded and
          - how the correction method is validated.
   f. Data analysis/data correction scripts (e.g., Jupyter Notebook, R Markdown).
   g. Location of final reported data and its format (e.g., data provided as .csv, website shows raw data and corrected data on user interface, expanded definitions of data headers).

7. Provide a warm-up and stabilization period for all the equipment (as specified by the manufacturer).

8. Confirm that all the equipment is reporting measurements.

9. For $PM_{2.5}$, document the particle size distribution and chemical composition of the particles used in the aerosol generator system.

10. Follow the manufacturer's maintenance recommendations for all equipment throughout Enhanced testing. Record and report all maintenance or troubleshooting performed on the

instruments including dates and times (e.g., power cycling, Reference Grade Monitor flow rate verification check, Reference Grade Monitor one-point QC check).

11. Initial Testing Conditions
    a. Set the exposure chamber to the conditions on Table 4.
    b. Allow all measurements to stabilize within the tolerances on Table 4.
    c. Once stabilized, collect either a minimum of 20 - 30 pairs of time-matched LCS and Reference Grade Monitor data points or three (3) consecutive hours[28] for:
        i. $PM_{2.5}$ concentration from each LCS ($\mu g/m^3$) or O_3 concentration from each LCS (ppbv).
        ii. Reference Grade Monitor $PM_{2.5}$ concentration ($\mu g/m^3$) or O_3 concentration (ppbv).
        iii. RH (%)
        iv. T (°C)

Table 4. Initial Testing Conditions for $PM_{2.5}$ and O_3

Parameter	Fine Particulate Matter (PM2.5)	Ozone (O3)
Concentration	35 $\mu g/m^3$ ± 5%	70 ppbv ± 5%
Temperature (T)	20°C ± 1°C	
Relative Humidity (RH)	40% ± 5%	

Adapted (US EPA, 2021).

12. Effect of Interferents:
    For O_3, follow the following steps to evaluate the effect on the LCSs performance in the presence of CO, NO_2, and SO_2:
    a. Repeat the steps under numeral 11, Initial Testing Conditions.
    b. After steady state is achieved (as described in Table 4), supply one single interferent pollutant to the exposure chamber at the concentration on Table 5. Adjust the exhaust to prevent pressure buildup as the total gas flow rate to the chamber changes.
    c. Allow all measurements to stabilize and allow the interferent pollutant concentration to reach the level within the tolerances described in Table 5.
    d. Once stabilized, collect either a minimum of 20-30 pairs of time-matched LCS and Reference Grade Monitor data points or three (3) consecutive hours for:
        i. O_3 concentration from each LCS (ppbv).
        ii. Reference Grade Monitor O_3 concentration (ppbv).
        iii. Interferent concentration (ppbv or ppmv).
        iv. RH (%)
        v. T (°C)

---

[28] "A pair of high time resolution instruments (LCS and FEM both reporting 1-minute averages) could collect 20 or more pairs of time-matched data quickly thereby minimizing the cost and duration of the test. A chamber using an FEM that only reports hourly averaged data would require a day to collect 20 time-matched data pairs but maintaining steady state conditions for that long would be extremely difficult, if not impossible. However, 3 time-matched data pairs (3 hours of testing) would provide a minimum number of data points for a statistical analysis. Testers should collect as many time-matched data pairs as possible, within the constraints of the testing setup, with a suggestion that 20-30 time-matched data pairs would be an ideal dataset." (US EPA, 2021).

e. Flush the exposure chamber with zero air until the interferent pollutant concentration reads zero ppbv or ppmv.

f. Repeat steps 12.a to 12.e under the Steps for Enhanced Testing section, for each interferent pollutant shown in Table 5.

Table 5. Interferent Pollutant Test Concentrations.

Interferent Pollutant	Reference Setpoint
CO	35 ppmv ± 5%
NO$_2$	100 ppbv ± 5%
SO$_2$	75 ppbv ± 5%

US EPA, 2021.

13. <u>Effect of elevated Relative Humidity:</u>

a. Repeat the steps on numeral 11. Initial Testing Conditions under the Steps for Enhanced Testing section.

b. Supply the exposure chamber with the conditions in Table 6.

c. Allow all measurements to stabilize within the tolerances described in Table 6.

d. Once stabilized, collect either a minimum of 20-30 pairs of time-matched LCS and Reference Grade Monitor data points or three (3) consecutive hours for:

   i.   PM$_{2.5}$ concentration from each LCS (μg/m^3) or O$_3$ concentration from each LCS (ppbv).

   ii. Reference Grade Monitor PM$_{2.5}$ concentration (μg/m^3) or O$_3$ concentration (ppbv).

   iii. RH (%)

   iv. T (°C)

Table 6. Elevated Relative Humidity Testing Conditions for PM$_{2.5}$ and O$_3$

Parameter	Fine Particulate Matter (PM$_{2.5}$)	Ozone (O$_3$)
Concentration	35 μg/m^3 ± 5%	70 ppbv ± 5%
Temperature (T)	20°C ± 1°C	
Relative Humidity (RH)	85% ± 5%	

Adapted (US EPA, 2021).

14. <u>Effect of elevated Temperature:</u>

a. Repeat the steps on numeral 11. Initial Testing Conditions under the Steps for Enhanced Testing section.

b. Supply the exposure chamber with the conditions in Table 7.

c. Allow all measurements to stabilize within the tolerances described in Table 7.

d. Once stabilized, collect either a minimum of 20-30 pairs of time-matched LCS and Reference Grade Monitor data points or three (3) consecutive hours for:

   i.   PM$_{2.5}$ concentration from each LCS (μg/m^3) or O$_3$ concentration from each LCS (ppbv).

    ii.   Reference Grade Monitor $PM_{2.5}$ concentration ($\mu g/m^3$) or O_3 concentration (ppbv).

    iii. RH (%)

    iv. T (°C)

Table 7. Elevated Temperature Testing Conditions for $PM_{2.5}$ and O_3

Parameter	Fine Particulate Matter ($PM_{2.5}$)	Ozone (O_3)
Concentration	35 $\mu g/m^3$ ± 5%	70 ppbv ± 5%
Temperature (T)	40°C ± 1°C	
Relative Humidity (RH)	40% ± 5%	

Adapted (US EPA, 2021).

15. Drift:

Drift can be evaluated at two (2) different points in time[29]. The LCSs are exposed to different low and mid-level concentrations of the target pollutant during Day 1 and measurements are acquired. Then, the LCSs are operated for a 60-day period on ambient outdoor air. Lastly, aged measurements are acquired by exposing the LCSs to the concentrations from the Day 1 measurements.

    a. On Day 1, supply the exposure chamber with the conditions in Table 8.

    b. Allow all measurements to stabilize within the tolerances described in Table 8.

    c. Once stabilized, collect either a minimum of 20-30 pairs of time-matched LCS and Reference Grade Monitor data points or three (3) consecutive hours for:

        i. $PM_{2.5}$ concentration from each LCS ($\mu g/m^3$) or O_3 concentration from each LCS (ppbv).

        ii. Reference Grade Monitor $PM_{2.5}$ concentration ($\mu g/m^3$) or O_3 concentration (ppbv).

        iii. RH (%)

        iv. T (°C)

    d. Supply the exposure chamber with the conditions in Table 9.

    e. Allow all measurements to stabilize within the tolerances described in Table 9.

    f. Once stabilized, collect either a minimum of 20-30 pairs of time-matched LCS and Reference Grade Monitor data points or three (3) consecutive hours for:

        i. $PM_{2.5}$ concentration from each LCS ($\mu g/m^3$) or O_3 concentration from each LCS (ppbv).

        ii. Reference Grade Monitor $PM_{2.5}$ concentration ($\mu g/m^3$) or O_3 concentration (ppbv).

        iii. RH (%)

        iv. T (°C)

    g. Operate the LCSs for 60 consecutive days in ambient, outdoor air.

---

[29] "The 60-day drift was chosen to balance the needs for a sufficient length of time in order to measure potential drift with the need to be unduly burdensome. It may be informative to repeat the drift test as LCSs age providing additional data points at periodic intervals up to the expected lifespan of the sensor." (US EPA, 2021).

h. Following the 60-day period, repeat the steps on numeral 15. Drift, under the **Steps for Enhanced Testing** section.

Table 8. Low Concentration Drift Test Conditions for PM$_{2.5}$ and O$_3$

Parameter	Fine Particulate Matter (PM$_{2.5}$)	Ozone (O$_3$)
Concentration	10 µg/m^3 ± 10%	15 ppbv ± 10%
Temperature (T)	20°C ± 1°C	
Relative Humidity (RH)	40% ± 5%	

Adapted (US EPA, 2021).

Table 9. Mid Concentration Drift Test Conditions for PM$_{2.5}$ and O$_3$

Parameter	Fine Particulate Matter (PM$_{2.5}$)	Ozone (O$_3$)
Concentration	35 µg/m^3 ± 5%	70 ppbv ± 5%
Temperature (T)	20°C ± 1°C	
Relative Humidity (RH)	40% ± 5%	

Adapted (US EPA, 2021).

16. Accuracy at High Concentrations:
    a. Supply the exposure chamber with the conditions in Table 10. For high PM$_{2.5}$, use the concentration of 150 µg/m^3.
    b. Allow all measurements to stabilize within the tolerances described in Table 10.
    c. Once stabilized, collect either a minimum of 20-30 pairs of time-matched LCS and Reference Grade Monitor data points or three (3) consecutive hours for:
        i. PM$_{2.5}$ concentration from each LCS (µg/m^3) or O$_3$ concentration from each LCS (ppbv).
        ii. Reference Grade Monitor PM$_{2.5}$ concentration (µg/m^3) or O$_3$ concentration (ppbv).
        iii. RH (%)
        iv. T (°C)
    d. As an optional test (if the objective of the study is higher concentrations of PM$_{2.5}$, such as the ones in smoke conditions), repeat steps 16.a to 16.c under the **Steps for Enhanced Testing** section, using the PM$_{2.5}$ higher concentration of 250 µg/m^3.

Table 10. High Concentration PM$_{2.5}$ and O$_3$ Test

Parameter	Fine Particulate Matter (PM$_{2.5}$)	Ozone (O$_3$)
Concentration	• High concentration: 150 µg/m^3 ± 5% • Higher concentration: 250 µg/m^3 ± 5%	125 ppbv ± 5%
Temperature (T)	20°C ± 1°C	
Relative Humidity (RH)	40% ± 5%	

Adapted (US EPA, 2021).

Metrics for Performance Characteristics: How to Calculate

After having defined some of the most relevant performance characteristics and the testing protocols to collect the data, now the equations used to estimate performance characteristics are presented. These equations are intended to be used for the data collected under the base testing and Enhanced testing Protocols as defined by US EPA, 2021 (see sections Base Testing and Enhanced Testing).

It is important to remember that to compare the data obtained from different instruments (i.e., from LCSs, Reference Grade Monitors, relative humidity and temperature sensors), the data streams need to be time aligned and close attention should be given to determine if data averages are time ending or time beginning (see more detail in section Data considerations).

Calculations for Base Testing Protocol

Daily and Hourly Averages (Base testing protocol)
For data reported as sub-daily time intervals (in the case of $PM_{2.5}$) or as sub-hourly time intervals (for O_3) by the a Reference Grade Monitor, LCS, and relative humidity or temperature sensors, there will be a need to average up to daily (for $PM_{2.5}$) or hourly (for O_3) averages (see Equation 1). This is because for base testing the performance metrics are calculated from daily (24-hour) averaged data for $PM_{2.5}$ and from hourly averaged data for O_3.

Of high importance is the fact that to calculate the averages, a 75% data completeness is required. That means that for $PM_{2.5}$ a LCS recording a data point every hour would need at least 18 valid measurements to be able to calculate a valid 24-hour averaged concentration. In the case of O_3, a LCS recording a data point every 15 minutes would require at least 3 valid measurements.

$$x_{kj} = \frac{1}{n} \sum_{i=1}^{n} c_{ij}$$

Equation 1

where:

x_{kj} is the averaged measurement (either 24-hour or 1-hour averaged) k for the corresponding day or hour and instrument j ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3, °C, %RH)

n is the number of instrument measurements per period of time

c_{ij} is the measurement from instrument j for time i of the time period ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3), °C, %RH)

Deployment Averages (Base testing protocol)
Deployment average concentrations and meteorological parameters for the base testing protocol should be reported as well, by calculating them from valid averaged data (either 24-hour averaged for $PM_{2.5}$ or

1-hour averaged for O_3). The calculation should be performed for each field test as shown in Equation 2 below.

$$\overline{x_k} = \frac{1}{M} \sum_{j=1}^{M} \left[\frac{1}{N} \sum_{t=1}^{N} x_{tj} \right]$$

Equation 2

where:

$\overline{x_k}$ is the deployment averaged measurement k for a field test ($\mu g/m^3$ for PM$_{2.5}$ or ppbv for O_3, °C, %RH)

M is the number of identical instruments operated simultaneously during a field test

N is the number of periods during which all identical instruments are operating and returning valid averages over the duration of the field test

x_{tj} is the valid time averaged (either 24-hour or 1-hour) measurement for either day or hour t and instrument j ($\mu g/m^3$ for PM$_{2.5}$ or ppbv for O_3, °C, %RH)

Precision (Base testing protocol)

Precision between identical LCSs will be determined by calculating both the standard deviation (SD, see Equation 3) between measurements and the coefficient of variation (CV, see Equation 4). The data used should be taken by identical LCSs operating and returning valid averaged data measurements (either 24-hour averaged for PM$_{2.5}$ or 1-hour averaged for O_3).

$$SD = \sqrt{\frac{1}{(N \times M) - 1} \sum_{j=1}^{M} \left[\sum_{t=1}^{N} (x_{tj} - \bar{x}_t)^2 \right]}$$

Equation 3

where:

SD is the standard deviation of the time averaged LCS pollutant concentration (either PM$_{2.5}$ or O_3) measurements ($\mu g/m^3$ for PM$_{2.5}$ or ppbv for O_3)

M is the number of identical LCSs operated simultaneously during a field test

N is the number of time periods (either 24-hour or 1-hour) during which all identical instruments are operating and returning valid averages over the duration of the field test

x_{tj} is the time averaged(either 24-hour or 1-hour) LCS pollutant concentration (either PM$_{2.5}$ or O_3) for either day or hour t and LCS j ($\mu g/m^3$ for PM$_{2.5}$ or ppbv for O_3)

$\bar{x}_t$ is the time averaged (either 24-hour or 1-hour) LCS pollutant concentration (either PM$_{2.5}$ or O_3) for time period t from the three (3) LCS ($\mu g/m^3$ for PM$_{2.5}$ or ppbv for O_3)

$$CV = \frac{SD}{\bar{x}} \times 100$$

Equation 4

where:
CV is the coefficient of variation (%)
SD is the standard deviation of the time averaged (either 24-hour or 1-hour) LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) measurements (µg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)
$\bar{x}$ deployment averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) for a field test (µg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

Bias and Linearity (Base testing protocol)
It is recommended to use a simple linear regression model for each identical LCS (y = mx + b) with corresponding graphical figures, using caution in selecting the Reference Grade Monitor pollutant measurements (either PM$_{2.5}$ or O$_3$) as the independent variable (x) and the LCS pollutant measurements (either PM$_{2.5}$ or O$_3$) as the dependent variable (y). Calculate the slope (m), intercept (b) and the coefficient of determination (R^2). LCS with similar regression models and high R^2 values (close to 1) are typically more precise than those with different regression models and low R^2 values, therefore comparing figures and these metrics between identical LCSs can help further visualize LCS precision.

Error (Base testing protocol)
A metric that can be used for determining error in LCS concentration measurements is the root mean square error (RMSE). The Reference Grade Monitor measurements are compared with data during which all LCSs are reporting valid time averaged data (either daily or hourly), assuming only one Reference Grade Monitor will be running. When using multiple Reference Grade Monitors, use separate reports for each.

It is important to clarify that RMSE is defined in two ways: describing the difference between the measurement and its true value or describing the difference between the measurement and a linear regression best fit line of a measurement and a corresponding true value. The former is used in this document (see Equation 5), since the US EPA indicates it is presumed to be the best indication of out-of-the-box LCS performance and the error that can be expected prior to any data corrections, as well as being how the RMSE is calculated in LCS literature to date.

$$RSME = \sqrt{\frac{1}{N \times M} \sum_{j=1}^{M} \left[\sum_{t=1}^{N} (x_{tj} - R_t)^2 \right]}$$

Equation 5

where:
$RSME$ is the root mean square error (µg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)
N is n number of valid time periods (either 1-day or 1-hour) during which all identical instruments are operating and returning valid averages over the duration of the field test
M is the number of identical LCSs operated simultaneously during a field test
x_{tj} is the time averaged (either 24-hour or 1-hour) LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) for day or hour t and instrument j (µg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

R_t is the valid time averaged (either 24-hour or 1-hour) Reference Grade Monitor pollutant concentration (either PM$_{2.5}$ or O$_3$) for day or hour t (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

Additionally, the normalized root mean square error (NRMSE, see Equation 6) can be used for ambient conditions where concentrations are very high (e.g., wildfires for PM$_{2.5}$).

$$NRMSE = \frac{RMSE}{\overline{R_t}} \times 100 \qquad\qquad \text{Equation 6}$$

where:
$NRMSE$ is the normalized root mean square error (%)
$RMSE$ is the root mean square error as calculated in Equation 5 (μg/m^3)
$\overline{R_t}$ is the 24-hour averaged Reference Grade Monitor pollutant concentration of PM$_{2.5}$ over the entire testing period (μg/m^3)

Dew Point and Effect of Meteorology (Base testing protocol)
As seen in previous sections, meteorology can affect the response of LCSs, in particular relative humidity, temperature and dew point. It is recommended to develop graphs that can help visualize those effects on measured concentrations by plotting the LCS measurements in the vertical axis, as the dependent variable and the meteorological parameters (as measured by relative humidity and temperature monitors, rather than by on-board relative humidity and temperature LCS measurements) as the independent variable on the horizontal axis. In order to develop the graphs to analyze the effect of meteorology, presented below are the equations to obtain normalized concentrations (i.e., the ratio of LCS to Reference Grade Monitor's concentration), concentration difference, absolute concentration difference and dew point (all these equations assume only one Reference Grade Monitor will be running; when using multiple Reference Grade Monitors, use separate reports for each).

Normalized Concentration (Base testing protocol)
To obtain the normalized 24-hour or 1-hour concentrations, divide the time averaged LCS pollutant concentration by the paired time averaged Reference Grade Monitor pollutant concentration as shown in Equation 7.

$$NormC_{tj} = \frac{x_{tj}}{R_t} \qquad\qquad \text{Equation 7}$$

where:
$NormC_{tj}$ is the normalized time averaged (either 24-hour or 1-hour) LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) from day or hour t and instrument j (unitless)
x_{tj} is the valid time averaged (either 24-hour or 1-hour) LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) from day or hour t and instrument j (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

R_t is the valid time averaged (either 24-hour or 1-hour) Reference Grade Monitor pollutant concentration (either PM$_{2.5}$ or O$_3$) from day or hour t (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

Concentration difference (Base testing protocol)
The concentration difference is obtained by subtracting the time averaged Reference Grade Monitor pollutant concentration from the time averaged LCS pollutant concentration, as shown in Equation 8.

$$\Delta C_{tj} = x_{tj} - R_t \qquad\qquad \text{Equation 8}$$

where:
ΔC_{tj} is the concentration difference between valid time averaged (either 24-hour or 1-hour) LCS and Reference Grade Monitor pollutant concentration (either PM$_{2.5}$ or O$_3$) values for day or hour t and LCS j (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)
x_{tj} is the valid time averaged (either 24-hour or 1-hour) LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) values for day or hour t and LCS j (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)
R_t is the valid time averaged (either 24-hour or 1-hour) Reference Grade Monitor pollutant concentration (either PM$_{2.5}$ or O$_3$) for day or hour t (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

Absolute Concentration Difference (Base testing protocol)
The absolute concentration difference is obtained by taking the absolute value of the difference between the time averaged LCS pollutant concentration and the time averaged Reference Grade Monitor pollutant concentration, as shown in Equation 9.

$$Abs\Delta C_{tj} = \left| x_{tj} - R_t \right| \qquad\qquad \text{Equation 9}$$

where:
AbsΔC_{tj} is the absolute concentration difference between valid time averaged (either 24-hour or 1-hour) LCS and Reference Grade Monitor pollutant concentration (either PM$_{2.5}$ or O$_3$) values for day or hour t and LCS j (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)
x_{tj} is the valid time averaged (either 24-hour or 1-hour) LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) values for day or hour t and LCS j (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)
R_t is the valid time averaged (either 24-hour or 1-hour) Reference Grade Monitor pollutant concentration (either PM$_{2.5}$ or O$_3$) for day or hour t (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

Dew Point (Base testing protocol)
The dew point (DP) is obtained from relative humidity (RH) and temperature (T) measurements (see Equation 10). As noted before, the RH and T measurements should be taken by sensors running alongside the LCS and the Reference Grade Monitors. Do not use measurements from on-board relative humidity

and temperature sensors, because those may not accurately represent ambient conditions of relative humidity and temperature.

$$DP_t = 243.04 \times \left[\frac{ln\left(\frac{RH_t}{100}\right) + \frac{(17.625 \times T_t)}{(243.04 + T_t)}}{17.625 - ln\left(\frac{RH_t}{100}\right) - \frac{(17.625 \times T_t)}{(243.04 + T_t)}} \right]$$ Equation 10

where:
DP_t is the valid time averaged (either 24-hour or 1-hour) ambient DP for day or hour t (°C)
RH_t is the valid time averaged (either 24-hour or 1-hour) ambient RH for day or hour t (%)
T_t is the valid time averaged (either 24-hour or 1-hour) ambient T for day or hour t (°C)

Additionally, below are some suggestions on plots that might be useful to visualize the effects of meteorology on LCS (US EPA, 2021). Other options may exist, but this list is presented since no specific plot has been demonstrated to be useful for all LCS types:

❖ Time averaged normalized LCS pollutant concentration vs. time averaged DP
❖ Time averaged normalized LCS pollutant concentration vs. time averaged RH
❖ Time averaged normalized LCS pollutant concentration vs. time averaged T
❖ Time averaged concentration difference between the LCS and Reference Grade Monitor pollutant concentration vs. time averaged DP
❖ Time averaged concentration difference between the LCS and Reference Grade Monitor pollutant concentration vs. time averaged RH
❖ Time averaged concentration difference between the LCS and Reference Grade Monitor pollutant concentration vs. time averaged T
❖ Time averaged absolute concentration difference between the LCS and Reference Grade Monitor pollutant concentration vs. time averaged DP
❖ Time averaged absolute concentration difference between the LCS and Reference Grade Monitor pollutant concentration vs. time averaged RH
❖ Time averaged absolute concentration difference between the LCS and Reference Grade Monitor pollutant concentration vs. time averaged T

Additional optional scatterplots if O_3 interferent data is also available are listed below:
❖ 1-hour averaged normalized LCS O_3 concentration vs. 1-hour averaged CO
❖ 1-hour averaged normalized LCS O_3 concentration vs. 1-hour averaged NO_2
❖ 1-hour averaged normalized LCS O_3 concentration vs. 1-hour averaged SO_2
❖ 1-hour averaged absolute concentration difference between the LCS and Reference Grade Monitor O_3 concentration vs. 1-hour averaged CO
❖ 1-hour averaged absolute concentration difference between the LCS and Reference Grade Monitor O_3 concentration vs. 1-hour averaged NO_2

❖ 1-hour averaged absolute concentration difference between the LCS and Reference Grade Monitor O_3 concentration vs. 1-hour averaged SO2

❖ 1-hour averaged concentration difference between the LCS and Reference Grade Monitor O_3 concentration vs. 1-hour averaged CO

❖ 1-hour averaged concentration difference between the LCS and Reference Grade Monitor O_3 concentration vs. 1-hour averaged NO_2

❖ 1-hour averaged concentration difference between the LCS and Reference Grade Monitor O_3 concentration vs. 1-hour averaged SO_2

❖ 1-hour averaged Reference Grade Monitor O_3 concentration vs. 1-hour averaged NO_2

❖ 1-hour averaged Reference Grade Monitor O_3 concentration vs. 1-hour averaged SO_2

❖ 1-hour averaged Reference Grade Monitor O_3 concentration vs. 1-hour averaged CO

Calculations for Enhanced Testing Protocol

The equations to calculate performance characteristics for the Enhanced testing protocol are presented below.

Data Averages (Enhanced testing protocol)

The time interval chosen to average all data will be the one from the instrument with the lowest time resolution (e.g., when choosing between the 1-minute time resolution of a LCS, RH, and T sensors and the 10-minute time resolution of a Reference Grade Monitor, average all data to the 10-minute time resolution).

For $PM_{2.5}$ the enhanced testing allows a higher time resolution data than base testing, since it is difficult to maintain stable particle delivery for long periods of time (1-hour, 10-minute, 1-minute averages). The selected time resolution is defined as t in Equation 11. Averaged data requires a 75% data completeness, as for Base testing.

$$x_{ktj} = \frac{1}{n} \sum_{i=1}^{n} c_{ij}$$

Equation 11

where:

x_{ktj} is the averaged measurement k for the time interval t and instrument j (µg/m³ for $PM_{2.5}$ or ppbv, ppmv for O_3, °C, %RH)

n is the number of instrument measurements during time interval t

c_{ij} is the measurement from instrument j for time i of the time interval t (µg/m³ for $PM_{2.5}$ or ppbv, ppmv for O_3), °C, %RH)

Test Averages (Enhanced testing protocol)

The valid averaged data to calculate test averaged measurements for Equation 12 should be collected during the steady state period for each test.

$$\overline{x_k} = \frac{1}{M} \sum_{j=1}^{M} \left[\frac{1}{N} \sum_{h=1}^{N} x_{ktj} \right]$$

Equation 12

where:

$\overline{x_k}$ is the test averaged measurement k for the chamber test (µg/m³ for PM$_{2.5}$ or ppbv, ppmv for O$_3$, °C, %RH)

M is the number of identical instruments operated simultaneously during the chamber test

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

x_{ktj} is the valid averaged measurement for time interval t and instrument j (µg/m³ for PM$_{2.5}$ or ppbv, ppmv for O$_3$, °C, %RH)

Precision (Enhanced testing protocol)

Precision between identical LCSs will be determined by calculating both the standard deviation (SD, see Equation 13) between measurements and the coefficient of variation (CV, see Equation 14). The data used should be valid averaged data collected during the mid-concentration test condition during the post-aging (Day 60) drift test (see Drift: pg. 25).

$$SD = \sqrt{\frac{1}{(N \times M) - 1} \sum_{j=1}^{M} \left[\sum_{t=1}^{N} (x_{tj} - \bar{x}_t)^2 \right]}$$
Equation 13

where:

SD is the standard deviation of test averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) measurements (µg/m³ for PM$_{2.5}$ or ppbv for O$_3$)

M is the number of identical sensors operated simultaneously during the chamber test

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

x_{tj} is the averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) time interval t and LCS j (µg/m³ for PM$_{2.5}$ or ppbv for O$_3$)

$\bar{x}_t$ is the test averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) for time interval t (µg/m³ for PM$_{2.5}$ or ppbv for O$_3$)

$$CV_{Enhanced} = \frac{SD}{\bar{x}} \times 100$$
Equation 14

where:

$CV_{Enhanced}$ is the coefficient of variation (%)

SD is the standard deviation of the test averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) measurements (µg/m³ for PM$_{2.5}$ or ppbv for O$_3$)

$\bar{x}$ test averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) for the chamber test (µg/m³ for PM$_{2.5}$ or ppbv for O$_3$)

Bias and Linearity (Enhanced testing protocol)

It is recommended to use a simple linear regression model (y = mx + b) between paired averaged LCS and Reference Grade Monitor pollutant measurements. "Pooling the data collected during the steady state period of the low and mid concentration test conditions during the post-aging (Day 60) drift test and the high concentration test (see Accuracy at High Concentrations: pg 26) will reflect data collected under similar T and RH conditions"[30]. Set the Reference Grade Monitor pollutant measurements (either $PM_{2.5}$ or O_3) as the independent variable (x) and the LCS pollutant measurements (either $PM_{2.5}$ or O_3) as the dependent variable (y). Calculate the slope (m), intercept (b) and the coefficient of determination (R^2).

Error (Enhanced testing protocol)

A metric that can be used for determining error in LCS concentration measurements is the root mean square error (RMSE). Calculate it by using the valid averaged data collected during the mid-concentration test condition during the post aging (Day 60) drift test (see Drift: pg. 25). Compare the LCS and the Reference Grade Monitor measurement calculations as shown in Equation 15. This assumes that only one Reference Grade Monitor will be running. When using multiple Reference Grade Monitors, use separate reports for each. It is important to clarify that RMSE is defined in two ways: describing the difference between the measurement and its true value or describing the difference between the measurement and a linear regression best fit line of a measurement and a corresponding true value. The former is used in this document (see Equation 15), since the US EPA indicates it is presumed to be the best indication of out-of-the-box LCS performance and the error that can be expected prior to any data corrections, as well as being how the RMSE is calculated in LCS literature to date.

$$RSME = \sqrt{\frac{1}{N \times M} \sum_{j=1}^{M}\left[\sum_{t=1}^{N}\left(x_{tj} - R_t\right)^2\right]} \qquad \text{Equation 15}$$

where:

$RSME$ is the root mean square error ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)

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

M is the number of identical LCSs operated simultaneously during the chamber test

x_{tj} is the averaged LCS pollutant concentration (either $PM_{2.5}$ or O_3) time interval t and instrument j ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)

R_t is the averaged Reference Grade Monitor pollutant concentration (either $PM_{2.5}$ or O_3) for time t ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)

Additionally, the normalized root mean square error (NRMSE, see Equation 16) can be used for ambient conditions where concentrations are very high (e.g., wildfires for $PM_{2.5}$).

$$NRMSE = \frac{RMSE}{\overline{R_t}} \times 100 \qquad \text{Equation 16}$$

---

[30] US EPA, 2021.

where:

$NRMSE$ is the normalized root mean square error (%)

$RMSE$ is the root mean square error as calculated in Equation 15 (μg/m^3)

$\overline{R_t}$ is the valid test averaged Reference Grade Monitor pollutant concentration of PM$_{2.5}$ over the test period (μg/m^3)

Effects of Interferents (Enhanced testing protocol)

For O$_3$ Enhanced Testing, the effect of each interferent is the difference between the measurement taken during steady state at a prescribe concentration of O$_3$ and the one from the steady state when the prescribed concentrations of O$_3$ and the prescribed interferent is present (see Equation 17).

$$\overline{x_{int}} = \overline{x_{(O_3 + int)}} - \overline{x_{O_3}}$$
Equation 17

where:

$\overline{x_{int}}$ is the test averaged influence of the interferent on LCS measurements (ppmv or ppbv, dependent upon interferent)

$\overline{x_{(O_3 + int)}}$ is the test averaged LCS O$_3$ concentration for the portion of the chamber test when both O$_3$ and the interferent are present (ppmv or ppbv, dependent upon interferent)

$\overline{x_{O_3}}$ is the test averaged LCS O$_3$ concentration for the portion of the chamber test when only O$_3$ is present (ppmv or ppbv, dependent upon interferent)

Effect of Relative Humidity (Enhanced testing protocol)

The effect of RH is the difference between the collected data during steady state at a prescribed pollutant concentration at 40% RH and collected the data during steady state at the same prescribed pollutant concentration at 85% RH (see Equation 18).

$$\overline{x_{RH}} = \overline{x_{(RH=85\%)}} - \overline{x_{(RH=40\%)}}$$
Equation 18

where:

$\overline{x_{RH}}$ is the test averaged influence of the RH on LCS measurements (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

$\overline{x_{(RH=85\%)}}$ is the test averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) for the portion of the chamber test when RH is 85% (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

$\overline{x_{(RH=40\%)}}$ is the test averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) for the portion of the chamber test when RH is 40% (μg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

Effect of Temperature (Enhanced testing protocol)

The effect of T is the difference between the collected data during steady state at a prescribed pollutant concentration at 20°C and collected the data during steady state at the same prescribed pollutant concentration at 40°C (see Equation 19).

$$\overline{x_T} = \overline{x_{(T=40)}} - \overline{x_{(T=20)}}$$
<div align="right">Equation 19</div>

where:
$\overline{x_T}$ is the test averaged influence of the T on LCS measurements ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)
$\overline{x_{(T=40)}}$ is the test averaged LCS pollutant concentration (either $PM_{2.5}$ or O_3) for the portion of the chamber test when T is 40°C ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)
$\overline{x_{(T=20)}}$ is the test averaged LCS pollutant concentration (either $PM_{2.5}$ or O_3) for the portion of the chamber test when T is 20°C ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)

Drift (Enhanced testing protocol)

Drift is calculated as the difference in the measurements over the 60-day period, for both the low concentration and the mid concentration of the pollutant (see Equation 20).

$$\overline{x_{C_{drift}}} = \overline{x_{C(day=60)}} - \overline{x_{C(day=1)}}$$
<div align="right">Equation 20</div>

where:
$\overline{x_{C_{drift}}}$ is the test averaged LCS drift at pollutant (either $PM_{2.5}$ or O_3) concentration C (either 10 $\mu g/m^3$ or 35 $\mu g/m^3$ for $PM_{2.5}$ or 15 ppbv or 70 ppbv for O_3) over the course of 60 days ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)
$x_{C(day=60)}$ is the test averaged LCS pollutant (either $PM_{2.5}$ or O_3) concentration at pollutant concentration C (either 10 $\mu g/m^3$ or 35 $\mu g/m^3$ for $PM_{2.5}$ or 15 ppbv or 70 ppbv for O_3) after 60 days of operation following the start of the drift test ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)
$x_{C(day=1)}$ is the test averaged LCS pollutant (either $PM_{2.5}$ or O_3) concentration at pollutant concentration C (either 10 $\mu g/m^3$ or 35 $\mu g/m^3$ for $PM_{2.5}$ or 15 ppbv or 70 ppbv for O_3) at the beginning of the drift test ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)

Accuracy at High Concentration (Enhanced testing protocol)

The accuracy at high concentration is calculated as the difference between the LCS and the Reference Grade Monitor measurements during the high concentrations test (see Equation 21).

$$\overline{x_\Delta} = \overline{x_{LCS}} - \overline{x_{ref}}$$
<div align="right">Equation 21</div>

where:
$\overline{x_\Delta}$ is the test averaged difference between the LCS and the Reference Grade Monitor pollutant concentrations (either $PM_{2.5}$ or O_3) ($\mu g/m^3$ for $PM_{2.5}$ or ppbv for O_3)

$\overline{x_{LCS}}$ is the test averaged LCS pollutant concentration (either PM$_{2.5}$ or O$_3$) (µg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

$\overline{x_{ref}}$ is the test averaged Reference Grade Monitor pollutant concentration (either PM$_{2.5}$ or O$_3$) (µg/m^3 for PM$_{2.5}$ or ppbv for O$_3$)

Acceptability Criteria for LCSs

After performing the testing protocols and calculating the recommended performance characteristics, the LCS's data quality and performance can be evaluated by comparing the performance characteristics to the recommended target values (i.e., Acceptability Criteria), which have been developed by the US EPA based on current-state-of-the-science achievable ranges observed for LCS performance. The recommended target values have been defined for the results of the base testing protocol. No target values have been developed for results from the enhanced testing protocol "due to limited feasibility, lack of consensus regarding testing protocols, inconsistency in LCS evaluation results that can result due to the limited amount of data that will be collected and variation in the tester's choice of PM surrogate"[31]. The recommended target values for Base testing are presented in Table 11.

Table 11. Recommended Target Values (Acceptability Criteria) of PM$_{2.5}$ and O$_3$ LCSs for Base Testing (for use in NSIM applications)

Performance Characteristic	Metric	PM$_{2.5}$ Target Value	O$_3$ Target Value
Precision	Standard Deviation (SD) or	≤ 5 µg/m^3	≤ 5 ppbv
	Coefficient of Variation (CV)	≤ 30%	≤ 30%
Bias	Slope	1.0 ± 0.35	1.0 ± 0.2
	Intercept (b)	-5 ≤ b ≤ 5 µg/m^3	-5 ≤ b ≤ 5 ppbv
Linearity	Coefficient of Determination (R^2)	≥ 0.70	≥ 0.80
Error	Root Mean Square Error (RMSE) or	RMSE ≤ 7 µg/m^3 or	≤ 5 ppbv
	Normalized Root Mean Square Error (NRMSE)	NRMSE ≤ 30%	-

Adapted (US EPA, 2021).

Additionally, LCS users might want to consider the objectives of the data collection (i.e., their application area as described in Table 12), which can guide them in setting performance goals in terms of data completeness and the error on precision and bias. As the objectives of the specific project become more rigorous, the performance goals are also expected to have higher data quality and better performance of the LCSs used. Table 12 contains four application areas and their recommended target values and includes regulatory monitoring values for those performance goals for comparison purposes.

---

[31] US EPA, 2021.

Table 12. Additional Recommended Target Values as per Application Area for Data Completeness and Error in Precision and Bias

Application Area	Description of application area and Rationale for the Target Values	Pollutants	Precision and Bias Error	Data Completeness
Education and Information	LCSs are used as teaching tools. Data is used for raising awareness about air quality challenges. Measurement error is not as important as simply demonstrating that the pollutant exists in some wide range of concentration.	All	< 50%	≥ 50%
Hotspot Identification and Characterization	LCSs are used to map pollutants and determine emission sources. Higher data quality is needed here to ensure that not only does the pollutant of interest exist in the local atmosphere, but also at a concentration that is close to its true value.	All	< 30%	≥ 75%
Supplemental Monitoring	Supplemental monitoring might have value in potentially providing additional air quality data to complement existing Reference Grade Monitors. To be useful in providing such complementary data, it must be of sufficient quality to ensure that the additional information is helping to "fill in" monitoring gaps rather than making the situation less understood.	Criteria pollutants, Air Toxics (including VOCs)	< 20%	≥ 80%
Personal Exposure	LCSs are used to monitor a person's exposure to air pollution. Many factors can influence personal exposure to air pollutants. Precision and bias errors suggested here are representative of those reported in the scientific literature under a variety of circumstances. Error rates higher than these make it difficult to understand how, when, and why personal exposures have occurred.	All	< 30%	≥ 80%
Regulatory Monitoring	Process by which government and /or regulatory air quality agencies determine if an area is in compliance with air quality regulatory standards. Precise measurements are needed to ensure high quality data is being obtained to meet regulatory requirements.	O_3	< 7%	≥ 75%
		CO, SO_2	< 10%	
		NO_2	< 15%	
		$PM_{2.5}$, PM_{10}	< 10%	

Adapted (US EPA, 2014).

LCS information compilation

This section presents a compilation of information on LCS performance characteristics and other parameters that might be useful for users. References are provided for the data presented so that the reader can further look into these considerations when analyzing the information below. A list[32] of reports that might contain useful information regarding LCSs characteristics is provided below as well. It is important to highlight that this document was prepared with information available from some brands with free data on the web that, as an example, intends to present the prototype of characteristic data for these measuring instruments. However, it is not intended to cover the entire portfolio of products available on the market and it is recommended that authorities or persons interested in the use of these elements make their own analysis of the models that best suit their specific needs and conditions, such as experiment setup, calibration location and duration, among others.

- AIRLAB Microsensor Challenge 2021 edition
  (https://airlab.solutions/en/projets/challenge-microcapteurs-edition-2021-90)
- European Commission, Review of sensors for air quality monitoring
  (https://publications.jrc.ec.europa.eu/repository/handle/JRC116534)
- European Commission, Review of performance of Low-cost sensors for Air Quality Monitoring
  (https://publications.jrc.ec.europa.eu/repository/handle/JRC117372)
- European Commission, Evaluation of low-cost sensors for air pollution monitoring: effect of gaseous interfering compounds and meteorological conditions
  (https://op.europa.eu/en/publication-detail/-/publication/23e1a2c7-3c41-11e7-a08e-01aa75ed71a1/language-en)
- South Coast AQMD, Air Sensor Performance Evaluation Center
  (https://www.aqmd.gov/aq-spec)
- US EPA, Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors. Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications
  (https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=350785&Lab=CEMM)
- US EPA, Performance Testing Protocols, Metrics, and Target Values for Ozone Air Sensors. Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications
  (https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=350784&Lab=CEMM)
- US EPA, Air sensor toolbox
  (https://www.epa.gov/air-sensor-toolbox)
- US EPA, Evaluation of emerging air sensor performance
  (https://www.epa.gov/air-sensor-toolbox/evaluation-emerging-air-sensor-performance)
- US EPA, Sensor Evaluation Report
  (https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NERL&dirEntryId=277270&simpleSearch=1&searchAll=sensor+evaluation+report)
- US EPA, Evaluation of Field-deployed Low Cost PM Sensors
  (https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NERL&dirEntryId=297517)

---

[32] Retama, A., 2022.

Table 13. Compiled Information on PM$_{2.5}$ LCSs.

Manufacturer	Model	Principle	Measurement and Detection Range	Time Resolution	T and RH range	R^2	RMSE (µg/m^3)	Precision (CV, %)
Alphasense Ltd.	OPC-N2	L.S.S.	0.38–17 µm, 16 channels (number concentration) PM$_1$, PM$_{2.5}$, PM$_{10}$	1.4 s	-10–50 °C 0–95% (n.c.)	0.007** (PM2.5) 0.01** (PM10)		
	OPC-N3	L.S.S.	0–2000 µg/m^3 0.35–40 µm, 24 channels (Number concentration) PM$_1$, PM$_{2.5}$, PM$_{10}$, Temperature and RH	1 s	-10–50 °C 0–95% (n.c.)	0.75-0.81$^+$		
	OPC-R1	L.S.S.	0.35–12.4 µm 16 channels (number concentration), PM$_1$, PM$_{2.5}$, PM$_{10}$, Temperature and RH	1 s	-10–50 °C 0–95% (n.c.)			
Dylos Corp	DC1700 PM PM2.5/PM10 AQM	L.S.S.	0–10^6 Particle/cm^3 >0.5 and >2.5 µm and PM$_{2.5}$ and PM$_{10}$ in µg/m^3	60 s	n.a.			
	DC1100*		particle counts*	60 s	- 95%	0.548*		
Honeywell	HPMA115SO-XXX	L.S.S.	0–1000 µg/m^3 PM$_{2.5}$ in µg/m^3 (PM10 in µg/m^3 with additional programming)	n.a.	-10–50 °C 0–95% (n.c.)			
Met One	831 Aerosol Mass Monitor	Photometer	0–1.000 µg/m^3 >0.1 µm	60 s	0–50 °C 90%*	0.773*		
Nova Fitness	SDS011	L.S.S.	0–999.9 µg/m^3 0.3–10 µm	1 s	-20–60 °C <70%			
		L.S.S.	0–999.9 µg/m^3 0.3–10 µm	1 s	-20–60 °C <70%			
		L.S.S.	0–20 mg/m^3 1–100 µm	1 s	-20–60 °C <70%			
Plantower	PMSA003	L.S.S.	0–500 µg/m^3 0.3–1.0; 1.0–2.5; 2.5–10 µm in three channels	n.a.	n.a.			
	PMS 3003	L.S.S.	0.3–1.0; 1.0–2.5; 2.5–10 µm in three channels	n.a.	-10–60 °C 0–99%			
	PMS 5003	L.S.S.	n.a.	n.a.	n.a.			
	PMS 7003	L.S.S.	n.a.	n.a.	n.a.			

Manufacturer	Model	Principle	Measurement and Detection Range	Time Resolution	T and RH range	R^2	RMSE (µg/m^3)	Precision (CV, %)
Samyoung	PSML(LPO)	Photometer	0–900 µg/m^3 PM$_{2.5}$ and PM$_1$	1 s	-10–65 °C <95% (n.c.)			
Sharp	GP2Y1010AU0F	Photometer	n.a.	n.a.	-10–60 °C 10–90%			
	DN7C3CA006	Photometer	25–500 µg/m^3	n.a.	-10–60 °C 10–90%			
Shinyei	PPD42NJ	Photometer	>1 µm	n.a.	0–45 °C <95% (n.c.)			
	PPD60PV-T2	Photometer	>0.5 µm	n.a.	0–45 °C <95% (n.c.)			
	PPD20V	Photometer	>1 µm	n.a.	0–40 °C <95% (n.c.)			
	PPD71	Photometer	>0.5 µm	n.a.	-10–60 °C <95% (n.c.)			
	PMS-SYS-1			1 s	- 95%*	0.152*		
Winsen	ZH03B	Photometer	0–1000 µg/m^3	n.a.	-10–50 °C 0–85% (n.c.)			
AirBase	CanarIT*			20 s*	- 100%*	0.004*		
CairClip PM				60 s*	- 95%*	0.064*		
Carnegie Mellon Speck			Particle counts*	1 s*	- 90%*	0*		
RTI	MicroPEM		Particle counts*	10 s*	- 95%*	0.720*		
Purple Air	PA-II-SD		2-36 µg/m^3			0.81+	6.52+	0.89+
Sensit	RAMP		0-4 µg/m^3			0.91+	7.07+	8.67+
Vaisala	AQT420		1-5 µg/m^3			0.01+	6.98+	31.03+
Clarity	Node					0.84+	3.59+	13.32+
	Node S					0.77+	7.64+	4.62+

Adapted (Venkatraman Jagatha, J. et. al., 2021).

*US EPA, 2014.

** Williams, R., et. al., 2017. Performance Evaluation of the United Nations Environment Programme Air Quality Monitoring Unit. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-17/171, 2017.

+ US EPA, 2021.

References

C. Hoyos, Personal communication (AMVA Citizen Scientists: Experience of Monitoring Air Quality using Low Cost Sensors), May 3, 2022.

Commission for Environmental Cooperation (CEC). Feasibility Study: Expanding the use of volunteer observer networks and citizen science tools in North America to address gaps in precipitation and wildfire monitoring: Report 1. Networks Review. Montreal, 2020.

deSouza, P., Kahn, R., Stockman, T., Obermann, W., Crawford, B., Wang, A., Crooks, J., Li, J., and Kinney, P. Calibrating Networks of Low-Cost Air Quality Sensors. *Atmos. Meas. Tech. Discuss.* [preprint], https://doi.org/10.5194/amt-2022-65, in review, 2022.

Holder, A., Clements, A., and Barkjohn, K. (2022, February 16). *How to evaluate air sensors for smoke monitoring applications.* EPA Tools and Resources Webinar. US EPA Office of Research and Development, Online. 2022. https://www.youtube.com/watch?v=wnSioJem6jY

Liang, L. 2021. Calibrating low-cost sensors for ambient air monitoring: Techniques, trends, and challenges. *Environmental Research.* Volume 197. ISSN 0013-9351. https://doi.org/10.1016/j.envres.2021.111163.

Raheja, G., Sabi, K., Sonla, H., Kokou Gbedjangni, E., McFarlane, C., Gameli Hodoli, C., and Westervelt., D.M. A Network of Field-Calibrated Low-Cost Sensor Measurements of PM2.5 in Lomé, Togo, Over One to Two Years. *ACS Earth and Space Chemistry* 6 (4), 1011-1021. DOI: 10.1021/acsearthspacechem.1c00391

Retama, A. (2022, August 29th – September 1st). *Ensambles, calibración, cuidados y manejo de datos. Consideraciones de precisión y confiabilidad, incluyendo criterios de aceptabilidad para su uso [presetation].* Capacitación Técnica: Fortalecimiento de capacidades en el entendimiento del uso, funcionamiento y generación de información de calidad de aire con sensores de bajo costo en el marco de la colaboración PNUMA - Clean Air Institute, Online. 2022.

Tracking California, Comite Civico del Valle, and University of Washington. Guidebook for Developing a Community Air Monitoring Network: Steps, Lessons, and Recommendations from the Imperial County Community Air Monitoring Project. Richmond, CA., 2018.

United States Environmental Protection Agency (US EPA). Air Sensor Guidebook. Washington, D.C., 2014.

United States Environmental Protection Agency (US EPA). Performance Testing Protocols, Metrics, and Target Values for Ozone Air Sensors. Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications. Washington, D.C., 2021.

United States Environmental Protection Agency (US EPA). Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors. Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications. Washington, D.C., 2021.

Venkatraman Jagatha, J.; Klausnitzer, A.; Chacón-Mateos, M.; Laquai, B.; Nieuwkoop, E.; van der Mark, P.; Vogt, U.; Schneider, C. Calibration Method for Particulate Matter Low-Cost Sensors Used in Ambient Air Quality Monitoring and Research. *Sensors* 2021, 21, 3960. https://doi.org/10.3390/s21123960

Williams, R., T. Conner, A. Clements, V. Foltescu, V. Nthusi, J. Jabbour, D. Nash, J. Rice, A. Kaufman, A. Rourk, and M. Srivastava. Performance Evaluation of the United Nations Environment Programme Air Quality Monitoring Unit. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-17/171, 2017.

World Meteorological Organization (WMO). An update on low-cost sensors for the measurement of atmospheric composition. Geneva, 2021.