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Air Sensor Guidebook

Office of Research and Development
National Exposure Research Laboratory

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Executive Summary

This Air Sensor Guidebook has been developed by the U.S. EPA to assist those interested in potentially using lower cost air quality sensor technologies for air quality measurements. Its development was in direct response to a request for such a document following a recent scientific conference (Apps and Sensors for Air Pollution-2012). Low cost air quality sensors ($100-$2500) are now commercially available in a wide variety of designs and capabilities. This is an emerging technology area and one that is quickly evolving. Even so, their availability has resulted in questions from many as to how they might be used appropriately. This document attempts to provide useful information concerning some of those questions.

The use of sensors to meet a variety of needs ranging from educational programs to professional research data collections is described. A select market survey is provided here to inform the reader about the cost range and performance capability of commercially available air quality sensors. The document provides background information on common air pollutants such as those defined as “criteria pollutants” as well as select others. Useful information is provided in the guidebook relative to key considerations about selecting the most appropriate sensor for one’s need concerning these pollutants.

Professional air quality researchers are trained to look for various attributes in monitoring technologies. While this document is limited in its scope concerning this area, basic information is provided that should assist citizen scientists and others in making the most appropriate choices. A major component of this guidebook is a discussion about data quality considerations. Such topics as the need to calibrate sensors, determining the precision of the device’s response, its response bias, and other performance characteristics are explained in practical terms. Examples of such performance characteristics determinations are provided to assist the user in understanding these important concepts.

This guidebook does not attempt to answer every question the U.S. EPA has received about the selection and use of various sensor technologies. Sensor use must be considered on an individual basis and only following careful consideration of why the data is being collected and for what purpose. Extensive resources, nearly all easily obtained free through the internet, are highlighted in the document to assist potential sensor users in obtaining useful information as they consider the incorporation of sensor technology to meet a variety of applications.

1. Introduction

This Document

This document guides people who develop and use low cost, highly portable sensors through:

- Background information about air quality
- Uses for air quality data
- Considerations when using or developing air sensors
- Ways to identify the best technology for a specific application
- How to collect useful data
- Performance characteristics to consider

1.1 About This Document/Intended Audience

This document provides useful information for individuals who are interested in air quality monitoring using commercially available lower cost sensors. In this case, such a sensor is one typically costing <$2500 and capable of estimating air pollutant concentrations in a continuous fashion (on the order of seconds to a few minutes in elapsed time). Potential users include individuals such as sensor developers, citizen scientists, teachers, and students; community organizations such as neighborhood alliances and environmental justice groups; and federal, tribal, state, and local air quality agencies.

The document was developed with input from experts across many different disciplines within the air quality community, including air sensor developers, users, and potential user groups. The U.S. EPA and its technical experts have provided input on this document and the technology being discussed.

1.2 Air Quality

Air quality affects our health and our environment. Numerous scientific studies have linked air pollution to a broad range of health and welfare effects. Potential health effects associated with air pollution exposures include decreased lung function, aggravation of respiratory and cardiovascular diseases, and increased asthma incidence and severity among a variety of others[1]. The U.S. EPA routinely reports on several key pollutants relative to their sources and known ecological and human health effects (www.epa.gov/ncea/isa). As defined in these reports, air pollutants have the potential to impact our lives including damaging vegetation, causing health issues, decreasing visibility, and affecting global climate conditions.

[1] U.S. EPA (2009) Integrated science assessment for particulate matter. EPA/600/R-08/139F; U.S. EPA (2006) Air quality criteria for ozone and related photochemical oxidants (2006). EPA/600/R-05/004aF-cF; Long-term ozone exposure and mortality, *N Engl J Med* 360:1085-1095, March 12, doi: 10.1056/NEJMoa0803894; U.S. EPA (2008) Integrated science assessment for oxides of nitrogen – health criteria. EPA/600/R-08/071; U.S. EPA (2010) Integrated science assessment for carbon monoxide. EPA/600/R-09/019F.

Air pollution consists of a complex mixture of different chemical compounds in the form of solid particles (in a range of sizes), liquid droplets, and gases. Some of these pollutants are short-lived in the atmosphere (i.e. hours to days), while others are long-lived (i.e. years). The amount of time that a particular pollutant remains in the atmosphere depends on its reactivity with other substances and its tendency to deposit on a surface; these factors are governed by the pollutant form (i.e., chemical compound) and weather conditions including temperature, sunlight, precipitation, and wind speed.

Pollutants are emitted by a wide variety of man-made and naturally occurring sources. Examples of man-made sources include electricity-generating power plants, automobiles, and oil and gas production facilities. Natural pollutant sources include wildfires, dust storms, and volcanic eruptions, among others. Some pollutants, called primary pollutants, are emitted directly from a source (including particulate matter [PM], carbon monoxide [CO], nitrogen dioxide [NO_2], sulfur dioxide [SO_2], and lead [Pb]). Others also known as secondary pollutants are formed by chemical reactions and are often found downwind from the source. This group includes ozone [O_3] and some forms of particulate matter. Airborne pollutant concentrations vary significantly over space and time because of variations in local emissions, proximity to pollutant sources, and weather conditions.

1.3 Air Pollution Monitoring

The Environmental Protection Agency (EPA) has identified six “criteria pollutants” as pollutants of concern because of their impacts on health and the environment[2]. The criteria pollutants are ozone[3] (O_3), particulate matter[4] (PM), carbon monoxide[5] (CO), nitrogen dioxide[6] (NO_2), sulfur dioxide[7] (SO_2), and lead[8] (Pb). Under the Clean Air Act, the EPA has established primary and secondary National Ambient Air Quality Standards (NAAQS) for these six pollutants. Primary standards are designed to protect public health, particularly sensitive populations, while secondary standards are designed to protect the public welfare which includes the environment. If a geographical area does not meet one or more of the NAAQS, it is designated as a non-attainment area and must design a plan to meet the standard[9]. NAAQS concentration limits are shown in Table 2-2.

The current monitoring network for criteria pollutants is comprised of monitors that meet Federal Reference Method (FRM) or Federal Equivalent Method (FEM) requirements. Monitors are operated by state, local and tribal air pollution agencies across the United States to assess pollutant concentrations in relation to the NAAQS; a variety of instruments and techniques are needed to measure specific pollutants. Regulatory monitoring generally requires very sophisticated and well-established instrumentation to meet measurement accuracy requirements and an extensive set of procedures to ensure that data quality is sufficient. These requirements (e.g., calibration, maintenance, audits, data validation)[10] help ensure the collection

[2] http://www.epa.gov/airquality/urbanair/
[3] http://www.epa.gov/air/ozonepollution/
[4] http://www.epa.gov/air/particlepollution/
[5] http://www.epa.gov/airquality/carbonmonoxide/
[6] http://www.epa.gov/air/nitrogenoxides/
[7] http://www.epa.gov/air/sulfurdioxide/
[8] http://www.epa.gov/air/lead/
[9] http://epa.gov/oaqps001/greenbk/
[10] 40 CFR Part 53 and Part 58. See www.epa.gov/ttnamti1/40cfr53.html

of high-quality data. Refer to 40 CFR Parts 50, 53, 58, and the QA Handbook Volume II for activities/criteria for monitoring network data. The overall quality and credibility of measurements are determined by both the type of instrument and how it's operated.

National Air Toxics Trends Stations (NATTS) are set up across the United States to monitor air toxics. These stations ensure that quality data is collected in a consistent manner.[11]

Under the Clean Air Act, EPA also regulates a list of 187 hazardous air pollutants (HAPs), commonly referred to as **"**air toxics**."** Starting in 2003, the EPA worked with state and local partners to develop the NATTS program to monitor several air toxics. The principal objective of the NATTS network is to provide long-term monitoring data across representative areas of the country for priority pollutants, including benzene, formaldehyde, 1,3-butadiene, hexavalent chromium and polycyclic aromatic hydrocarbons (PAHs) such as naphthalene, in order to establish overall trends. Additionally, some regulated industrial sources are required to submit air toxics emissions information to the EPA. The quality and completeness of emissions data varies significantly by region and source. NATTS-related information can be found at http://www.epa.gov/ttnamti1/natts.html.

[11] http://www.epa.gov/ttnamti1/natts.html

To learn more about air pollutants in your neighborhood, you can access EPA's My Environment page ([www.epa.gov/enviro/myenviro)](http://www.epa.gov/enviro/myenviro). Information accessed on this site represents reported air pollutant data from industrial and other major sources. Sensor data, like that described in this report, are not reported on this website. In the box marked "Location," enter your zip code, and you will be able to view a wealth of environmental data (including information on air, water, land, energy, and health) specific to your location. The image below provides an example of the "My Environment" map, and the information it contains. The dark blue squares are air emission sources and the light blue squares are toxic releases to air.

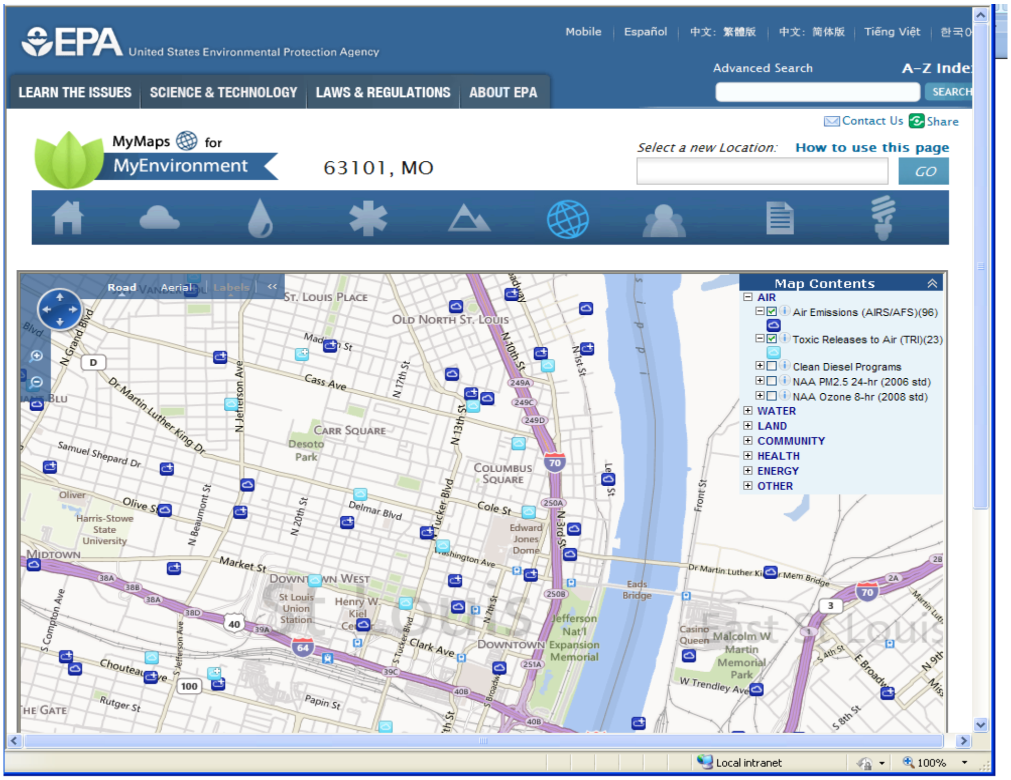

Figure 1-1. Example of the interactive My Environment map on EPA's website.

1.4 Uses for Air Sensors

The new generation of low-cost, highly portable air quality sensors is providing an exciting opportunity for people to use this technology for a wide range of applications beyond traditional regulatory or regulatory-equivalent monitoring. Air pollution sensors are still in an early stage of technology development, and many sensors have not yet been evaluated to determine the accuracy of their measurements. EPA has specific guidelines it must use in establishing regulatory-grade air monitors. No lower cost sensors currently meet these strict requirements or have been formally submitted to EPA for such a determination. Table 1-1 summarizes some potential non-regulatory application areas for air sensors and provides brief descriptions and examples. These application areas are described in more detail in Section 5.

Table 1-1. Descriptions of potential uses for low cost air sensors.

Application	Description	Example
Research	Scientific studies aimed at discovering new information about air pollution.	A network of air sensors is used to measure particulate matter variation across a city.
Personal Exposure Monitoring	Monitoring the air quality that a single individual is exposed to while doing normal activities.	An individual having a clinical condition increasing sensitivity to air pollution wears a sensor to identify when and where he or she is exposed to pollutants potentially impacting their health.
Supplementing Existing Monitoring Data	Placing sensors within an existing state/local regulatory monitoring area to fill in coverage.	A sensor is placed in an area between regulatory monitors to better characterize the concentration gradient between the different locations.
Source Identification and Characterization	Establishing possible emission sources by monitoring near the suspected source.	A sensor is placed downwind of an industrial facility to monitor variations in air pollutant concentrations over time.
Education	Using sensors in educational settings for science, technology, engineering, and math lessons.	Sensors are provided to students to monitor and understand air quality issues.
Information/Awareness	Using sensors for informal air quality awareness.	A sensor is used to compare air quality at people's home or work, in their car, or at their child's school.

Sensor performance requirements differ according to the application. The quality of a measurement is dictated by the basic performance of the sensor, the way the sensor is operated, and the way its measurements are analyzed. Understanding the strengths and limitations of an air sensor is important if that sensor is to collect information that is useful for a specific purpose.

2. Air Quality 101

This Section

- Introduces factors affecting air quality (such as type of pollutant, weather, and data collection location)
- Discusses how these factors relate to each other
- Explains how these factors may influence the way you use sensors
- Summarizes typical air pollutants, sources, health effects, and concentrations

2.1 Overview

"Air quality" is a term used to relate how much pollution is present in the air - good air quality means there is less air pollution, while poor air quality means there is more pollution. The U.S. EPA has developed a general guide for citizens called the Air Quality Index (http://airnow.gov/index.cfm?action=aqibasics.aqi) where pollutant concentrations and health concerns have been established for a number of common pollutants. We care about air quality because air pollutants can affect our health and our environment. An increasing number of studies link air pollution to a range of health problems. In 2010, with respect to the "criteria pollutants" (see section 1.3), over 120 million Americans lived in counties where concentrations exceeded the levels of one or more National Ambient Air Quality Standards (NAAQS)[12]. It must be pointed out that measuring a concentration value above a respective level of a standard does not necessarily mean an air pollutant violation has occurred. Multiple factors must be considered before a true violation of air quality can be established. In addition to causing adverse health effects, these pollutants can also cause adverse ecological effects such as impaired visibility or significant damage to plant life. Acidic pollutants deposited on the ground, predominantly in rain, harm both land and water ecology. Furthermore, many pollutants - including greenhouse gases (which trap heat in the atmosphere) and particles - also affect the Earth's energy balance, impacting climate[13].

Air pollution is a complex mixture of many different chemical compounds, which are emitted through human activity as well as natural events like wildfires and volcanos. Pollutants of concern in ambient (outdoor) air include ozone (O_3), sulfur dioxide (SO_2), oxides of nitrogen, carbon monoxide (CO), lead (Pb), ammonia (NH_3), volatile organic compounds (VOCs), mercury (Hg), and other toxic air pollutants. Also of concern are airborne particles, commonly referred to as particulate matter (PM). While these particles can range in size, they are typically characterized into one of two groups. A standard for PM_{10} particles has been established to provide protection for effects associated with thoracic coarse particles having diameters up to 10 micrometers. Such particles are commonly found near roadways and dusty industries. "Fine particles" (up to 2.5 micrometers in diameter, also known as $PM_{2.5}$) are emitted or formed

[12] www.epa.gov/airtrends/2011/
[13] http://www.epa.gov/climatechange/science/causes.html

through chemical reactions, fuel combustion (e.g., burning coal, wood, diesel), industrial processes, agriculture (plowing, field burning), and unpaved roads. As noted above in Section 1.3, ambient levels of particulate matter and other certain pollutants in the air (O_3, PM, SO_2, NO_2, CO, and Pb) are regulated by the EPA through the NAAQS. The term “ambient” relates to outdoor air used to identify air quality conditions in select locations identified by the EPA as being representative of a given geographical location. Typically such locations are not in close proximity to major air pollution sources.

2.2 Pollutant-Specific Effects on Health and the Environment

A broad range of health and environmental effects have been seen following exposures to air pollutants. Many air pollutants, can remain in the environment for long periods of time and are carried by the wind hundreds of miles from their origin. The effects resulting from various air pollutants may be seen/associated after short-term (hours to weeks) or long term exposures (months to years). Air pollution can also cause environmental harms, including climate change, acid rain, smog and haze. Table 2-1 summarizes health, environmental, and climate effects of common air pollutants.

Table 2-1. Health, environmental, and climate effects of common air pollutants: quality status and trends through 2008[14]).

Pollutant	Health Effects	Environmental and Climate Effects
Ozone (O_3)	Breathing ozone can trigger a variety of health problems including chest pain, coughing, throat irritation, and congestion. It can worsen bronchitis, emphysema, and asthma. Ground level ozone can also reduce lung function and inflame the linings of the lungs. Repeated exposure may permanently scar lung tissue.	Damages vegetation by injuring leaves, reducing photosynthesis, impairing reproduction and growth, and decreasing crop yields. Damage to plants may alter ecosystem structure, reduce biodiversity, and decrease plant uptake of carbon dioxide (CO_2). Ozone is a greenhouse gas that contributes to the warming of the atmosphere.
Particulate Matter (PM includes $PM_{2.5}$ and PM_{10})	Breathing particulate matter can cause premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, and increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing. Long- and short-term exposures to fine particles cause premature death and adverse cardiovascular effects, including increased hospitalizations and emergency department visits for heart attacks and strokes. Fine particle exposures are also linked to respiratory effects including increased hospital admissions and emergency department visits for respiratory effects, such as asthma attacks, as well as increased respiratory symptoms such as coughing, wheezing, and shortness of breath as well as reduced lung development in children. Short-term exposures to thoracic coarse particles are linked to premature death and hospital admissions and emergency department visits for heart and lung disease.	Impairs visibility, affects ecosystem processes, and can deposit onto surfaces damaging materials. Climate impacts: most particles are reflective and lead to net cooling, while some (especially black carbon) absorb energy and lead to warming.

[8] www.epa.gov/airtrends/2010/

Pollutant	Health Effects	Environmental and Climate Effects
Lead (Pb)	Damages the developing nervous system, resulting in IQ loss and negative impacts on children's learning, memory, and behavior. In adults, causes cardiovascular and renal effects and early effects related to anemia.	Lead is persistent in the environment and accumulates in soils and sediments through deposition from air sources, direct discharge of waste streams to water bodies, mining, and erosion. Ecosystems near point sources of lead demonstrate a wide range of adverse effects including losses in biodiversity, changes in community composition, decreased growth and reproductive rates in plants and animals, and neurological effects in vertebrates.
Sulfur Dioxide (SO_2)	Aggravates pre-existing respiratory disease in asthmatics leading to symptoms such as cough, wheeze, and chest tightness. Asthmatics are most at-risk, but very high levels can cause respiratory symptoms in people without lung disease. Exposures over longer time periods can result in hospital admissions and ED visits in the general population.	Contributes to the acidification of soil and surface water. Causes injury to vegetation and losses of local species in aquatic and terrestrial systems. Increases the bioavailability of mercury in surface waters which impacts fish and other wildlife. Contributes to particle formation, which has a net cooling effect on the atmosphere.
Nitrogen Dioxide (NO_2)	Aggravates respiratory symptoms, increases hospital admissions, and ED visits, particularly in asthmatics, children, and older adults; increases susceptibility to respiratory infection.	Contributes to the acidification and nutrient enrichment (eutrophication, nitrogen saturation) of soil and surface water. Leads to oxygen depletion in waters, losses of plants and animals, and changes in biodiversity losses. Impacts levels of ozone, particles, and methane with associated environmental and climate effects.
Carbon Monoxide (CO)	Reduces the amount of oxygen reaching the body's organs and tissues; aggravates heart disease, leading to hospital admissions and ED visits.	Contributes to the formation of CO_2 and ozone, greenhouse gases that warm the atmosphere.
Volatile Organic Compounds (VOCs)	Some are toxic air pollutants that cause cancer and/or other serious health problems. Contribute to ozone formation with associated health effects.	Contribute to ozone formation with associated environmental and climate effects. Also, contribute to the formation of CO_2 and secondary organic aerosols that can warm and cool the atmosphere, respectively.

Pollutant	Health Effects	Environmental and Climate Effects
Mercury (Hg)	Concerns center on bioaccumulation and methylation in fish consumed by humans. Methyl mercury poisoning causes neurological and developmental damage.	Deposits onto soil and into rivers, lakes, and oceans, where it accumulates in fish, resulting in harmful levels of exposure to humans and predatory wildlife.
Other Toxic Air Pollutants (e.g., Benzene)	May cause cancer; immune system damage; and neurological, reproductive, respiratory, developmental, and/or other health problems. Some contribute to ozone and particle pollution with associated health effects.	Harmful to wildlife and livestock. Some toxic air pollutants accumulate in the food chain. Some toxic air pollutants contribute to ozone and particle pollution with associated environmental and climate effects.

2.3 Important Air Quality Concepts and Characteristics

Air quality is a complex, multi-faceted topic with many nuances. Although it can take years to gain a comprehensive understanding of air pollution, there are some basic concepts and characteristics that can be learned quickly and provide a good foundation on which to build. Below is an overview of the most important concepts and characteristics to be aware of when making air quality measurements. For additional information on these concepts and characteristics, please consult Appendix B.

Choosing a location: Many pollutants have high spatial variability, that is, their concentration varies over long or even short distances. This makes sensor location an important consideration in the design of any monitoring study. Concentrations for most pollutants will almost always be highest near the source, and will decrease rapidly within the first few hundred feet of the source. If multiple sources are widely distributed within a given area, pollutant concentrations may be more similar but will still experience change from location to location. Other factors, including pollutant type and local atmospheric conditions (discussed below) will also influence the concentration variability of a given pollutant. Carefully locating your sensor will play a significant role in determining whether the data you have collected are representative and useful. Where and how to properly locate sensing devices is discussed further in Section 4.

Factoring in pollutant type: As discussed in Section 1.2, some pollutants may be emitted directly by a source (primary pollutants), while others may be formed as the products of chemical reactions in the air (secondary pollutants). Primary pollutants are often more localized (i.e. near the source) and may have a greater variability over distances than secondary pollutants. It is important to consider whether a pollutant of interest is primary or secondary when deciding where and how to collect monitoring data.

Whether a pollutant comes from man-made or natural sources (or both) is also an important consideration. While measurements typically focus on man-made sources of pollution, all known sources should be considered when designing a monitoring study. Pollutants coming from unknown sources can compromise the utility and accuracy of conclusions drawn from data.

Considering wind and atmospheric conditions: Meteorological processes - including sunlight, temperature, humidity and clouds - can affect pollutant concentrations. For example, stagnant air can lead to pollutant concentrations that gradually increase, whereas strong winds can decrease concentrations by spreading pollutants over a larger geographic area. Understanding how weather conditions can influence pollution concentration and data collection is important in gathering accurate information and interpreting trends in data.

Factoring in pollutant variation over time: Pollutant concentrations may vary significantly depending on the time of day, the day of the week, and the season. These differences can be attributed to changes in emissions patterns, temperature, the activity schedule of the source (weekly traffic patterns, for example), and differences in formational processes. Daily, weekly, and seasonal variations are important considerations when developing a measurement plan, and will guide the time and conditions under which measurements should be taken.

Sensor response time: This is a key attribute in determining whether true pollutant fluctuations can be captured. For capturing a quickly changing or short-lived pollutant plume, detection on the order of seconds may be important. In other applications, such as monitoring general outdoor air quality trends, detection at tens of minutes may be sufficient.

2.4 Atmospheric Pollutants, Their Sources, and Concentration Ranges to Expect

Table 2-2 summarizes select pollutants and information relevant to detecting these pollutants in air. Please note the following about the information provided in the columns of this table:

Air Pollutant of Interest: Pollutants in the table includes the gases: SO_2, NO_x, ozone, CO, CO_2, methane, VOCs, and benzene. Solid particle pollutants are: $PM_{2.5}$, PM_{10}, lead, and black carbon.

Type: Pollutants may be directly emitted (primary pollutants) or formed in the atmosphere by chemical reactions (secondary pollutants). CO, emitted directly from combustion processes (such as car exhaust), is an example of a primary pollutant. Ozone, formed by the reaction of NO_x and VOCs in the presence of sunlight, is a secondary pollutant. Some pollutants, such as particulate matter (PM), can have both primary (e.g., black carbon - the most strongly light-absorbing component of PM, formed by incomplete combustion[15]) and secondary (e.g., sulfate, nitrate) components.

Useful Detection Limits: A detection limit is the lowest concentration of a pollutant in the environment that a particular sensor or other instrument can routinely detect. The detection limits in the table are provided to inform citizen scientists of what sensor detection limits would be practically useful. Explanation of units and averaging periods:

$\mu g/m^3$ = microgram per cubic meter
ppm = parts per million
ppb = parts per billion
(1 hr) = one hour averaging time period
(8 hr) = one eight hour averaging time period
(24 hr) = one 24 hr averaging time period
(3 mo) = one three month averaging time period
(1 yr) = one year averaging time period

Range to expect: The table indicates average concentration ranges to expect in ambient air in the United States. Concentrations near sources (adjacent to and downwind of a major power plant or roadway, for instance) may at the upper end of the range, or even higher. On the other hand, pollution in an area that is not close to a specific source is more likely to be at the low end of the range.

[15] http://epa.gov/blackcarbon/basic.html

Level: A level is the airborne pollutant concentration that has been identified where concerns exist if exposure occurs for a defined period of time. These examples are provided for comparison purposes only. For air toxics, there are no NAAQS, but instead the table provides examples of exposure levels of concern. A complete list of air toxic values of concern is available at http://www.epa.gov/ttn/atw/hlthef/hapindex.html.

Table 2-2. Summary of some common air pollutants[16] -- See text on page 12 for explanation of column headings.

Air Pollutant of Interest[17]	Type	Source Example	Useful Detection Limits	Range to Expect	Level[18]
Ozone (O_3)	Secondary	Formed via UV (sunlight) and pressure of other key pollutants	10 ppb	0-150 ppb	75 ppb (8 hr)
Carbon monoxide (CO)	Primary	Fuel combustion – mobile sources, industrial processes	0.1 ppm	0-0.3 ppm	9 ppm (8 hr) 35 ppm (1 hr)
Sulfur dioxide (SO_2)	Primary	Fuel combustion – electric utilities, industrial processes	10 ppb	0-100 ppb	75 ppb (1 hr) 0.5 ppm (3 hr)
Nitrogen dioxide (NO_2)	Primary and Secondary	Fuel combustion – mobile sources, electric utilities, off-road equipment	10 ppb	0-50 ppb	100 ppb (1 hr) 53 ppb (1 yr)
Carbon dioxide (CO_2)[19]	Primary	Fuel combustion – electric utilities, mobile sources	100 ppm	350-600 ppm	None
Methane (CH_4)[20]	Primary	Industry (e.g., natural gas operations), agriculture, and waste management	500 ppb	1500-2000 ppb	None
Volatile organic compounds (VOCs)[21]	Primary and Secondary	Fuel combustion (mobile sources, industries) gasoline evaporation; solvents	1 µg/m^3	5-100 µg/m^3 (total VOCs)	None

[16] Table adapted from EPA's Draft Roadmap for Next Generation Air Monitoring http://www.epa.gov/research/airscience/docs/roadmap-20130308.pdf.
[17] Information on pollutants is available at http://www.epa.gov/airquality/ and http://www.epa.gov/airtrends/
[18] See http://epa.gov/air/criteria.html for additional information on a select number of the pollutants listed here. If must be recognized that multiple factors must be considered in establishing a pollutant concentration of concern in addition to just the averaging time. Various statistical data treatments are often required and the information in this column is not fully descriptive of these issues.
[19] http://www.epa.gov/climatechange/ghgemissions/gases/co2.html.
[20] http://epa.gov/climatechange/ghgemissions/gases/ch4.html.
[21] http://www.epa.gov/ttn/amtic/pamsmain.html.

Air Pollutant of Interest[17]	Type	Source Example	Useful Detection Limits	Range to Expect	Level[18]
Benzene (an example of a VOC and air toxic)[22]	Primary	Gasoline, evaporative losses from above ground storage tanks	0.01 – 10 µg/m³	0-3 µg/m³	None
Fine particulate matter ($PM_{2.5}$)	Primary and Secondary	Fuel combustion (mobile sources, electric utilities, industrial processes), dust, agriculture, fires	5 µg/m³ (24-hr)	0-40 µg/m³ (24-hr)	35 µg/m³ (24 hr) 12 µg/m³ (1 yr)
Particulate matter (PM_{10})	Primary and Secondary	Dust, fuel combustion (mobile sources, industrial processes), agriculture, fires	10 µg/m³ (24-hr)	0-100 µg/m³ (24-hr)	150 µg/m³ (24 hr)
Lead (Pb)	Primary	Smelting, aviation gasoline, waste incinerators, electric utilities, and lead-acid battery manufacturers	0.05 µg/m³ (24-hr)	0-0.1 µg/m³ (24-hr)	0.15 µg/m³ (3 mo)
Black carbon (BC)[23]	Primary	Biomass burning, diesel engines	0.05 µg/m³	0-15 µg/m³	None

It should be recognized that there are certain circumstances in which concentrations above those discussed in Table 2.2 are permissible, especially under occupational settings. The National institute of Occupational Safety and Health (NIOSH) has established guidelines for such circumstances that sensor users also need to consider in determining data collection plans. For example, the NAAQS indicates that CO levels at the 35 ppm level for a 1 hour period warrants potential health concerns (ambient air), the NIOSH has established guidelines indicating that occupational exposures of 35 ppm (8 hour exposure time period) with a 200 ppm maximum (at any time) must be considered. Therefore, sensor users should be aware that just because a measurement exceeds the EPA ambient standard that a violation of air quality might not exist. The circumstances must be considered. In other words, there are legitimate circumstances where airborne concentrations higher than the NAAQS are permitted. Sensor users are suggested to view information on the NIOSH web link provided below that provides specific guidelines on occupational settings and allowable concentrations for a wide variety of air pollutants.

http://www.cdc.gov/niosh/npg/npgd0105.html

[22] http://www.epa.gov/ttnatw01/hlthef/benzene.html.
[23] http://www.epa.gov/blackcarbon/basic.html.

2.5 Health Implications of Air Quality Measurements

As described in Table 2-1, air pollution can have a number of serious health impacts. For all of the criteria pollutants except lead, EPA has established the Air Quality Index (AQI) as a means to translate pollution measurements into the potential for effects in individuals. The AQI is an index for reporting daily air quality. It tells you how clean or polluted your air is, and what associated health effects might be a concern for you. The AQI focuses on health effects you may experience within a few hours or days after breathing polluted air. EPA calculates the AQI for five major air pollutants regulated by the Clean Air Act: ground-level ozone, particle pollution (also known as particulate matter), carbon monoxide, sulfur dioxide, and nitrogen dioxide. For each of these pollutants, EPA has established national air quality standards to protect public health. Ground-level ozone and airborne particles are the two pollutants that pose the greatest threat to human health in this country. EPA uses information based on ambient ozone concentrations in the determination of the daily AQI. On-line formulas incorporate information such as observed 24-hr average concentrations and established minimum and maximum pollutant ranges. Easy to use on-line calculators are available that allow individuals to either calculate a local AQI or back calculate the reported AQI to estimated pollution levels.[24]

Air Quality Index Levels of Health Concern	Numerical Value	Meaning
Good	0 to 50	Air quality is considered satisfactory, and air pollution poses little or no risk
Moderate	51 to 100	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is not likely to be affected.
Unhealthy	151 to 200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
Very Unhealthy	201 to 300	Health warnings of emergency conditions. The entire population is more likely to be affected.
Hazardous	301 to 500	Health alert: everyone may experience more serious health effects

Figure 2-1. The Air Quality Index (AQI) levels of health concern, numerical values, and meanings.

[24] http://airnow.gov/index.cfm?action=aqibasics.aqi

However, it's important to understand that the AQI is calculated based on air pollution data that is averaged over 1, 8, or 24 hours, depending on the pollutant (see Table 2-2). The reason for the different averaging times is that different pollutants affect the human body in different ways. For example, SO_2 can cause difficulty breathing and respiratory symptoms such as cough, wheeze, and chest tightness within 5 minutes of exposure. This is because SO_2 affects the parts of your lungs that communicate with your central nervous system, triggering a reflex response that can quickly cause a narrowing of the airways (called bronchoconstriction). Importantly, the SO_2 NAAQS has already taken into account the speed at which SO_2 can cause these respiratory effects. That is, the level of the *1-hour* SO_2 NAAQS was set low enough to provide substantial protection against the much higher *5-minute* concentrations that can cause these effects. Because the AQI for SO_2 is based on the 1-hour NAAQS, it can effectively communicate when the air is healthy or unhealthy to breath. Those most susceptible to the effects of SO_2 are asthmatics who exercise, work, or play outdoors.

While SO_2 can affect the respiratory system within minutes, the respiratory effects of O_3 can happen in an hour or so, or may not occur until the next day. Again, this is because of the specific way that O_3 affects the body. Ozone can reduce lung function, but based on a person's antioxidant status and the O_3 dose inhaled, it may take an hour or more for symptoms such as bronchoconstriction to occur. Ozone can also inflame and damage the lining of the lung, but this effect may not be most obvious until the day after exposure. Some scientists have compared ozone's inflammatory effect on the lining of the lung to the inflammatory effect of sunburn on the skin. Ozone damages the cells that line the air spaces in the lung. Within a few days, the damaged cells are replaced and the old cells are shed- much in the way that skin peels after a sunburn. Also like a sunburn, the effects can be worse later the same day or the next day, and it can take your lungs a while to recover. And, if this kind of damage occurs repeatedly, the lung may change permanently in a way that could cause long-term health effects and a lower quality of life. Similar to the SO_2 NAAQS, the 8-hour O_3 NAAQS provides substantial protection against these respiratory effects by taking into account the way O_3 interacts with the body.

With respect to my health, what do my sensor readings mean?

Some citizen scientists may become concerned if they measure levels of a pollutant higher than the health benchmarks provided in Table 2-2. However, it is very important for the user to consider the time period over which the pollutant level was measured. For example, the daily (24 hour) $PM_{2.5}$ standard is 35 ug/m^3. Because the standard is based on the average of hourly monitoring measurements over a 24-hour period, it does not mean that a single $PM_{2.5}$ measurement taken over a few minutes, or even hours, above 35 ug/m^3 is cause for immediate concern. By using the AQI calculator on the EPA website, you can learn that a 24-hour average measurement of $PM_{2.5}$ of 35 ug/m^3 is "yellow," or moderate air quality, and a 24-hour average measurement of 50 ug/m^3 is "orange," or unhealthy for sensitive groups. Again, for the AQI, it is very important to remember that the concentration that you enter into the calculator is meant to be an average value over a longer time period, (in this example, over 24 hours) not just a single reading taken over the span of a few minutes or hours.

The increasing use of sensors is expected to provide more data on air pollution than has previously been available, and in shorter time increments. For example, it will be much easier to track minute-by-minute changes in pollution levels. As a result, we will become more aware of short-term, peak levels of some pollutants. However, the actual health effects of very short term elevated levels of most pollutants are not well understood and EPA has not established health information defining such short-term pollutant exposures.

This document *does not* provide detailed guidance on health-based interpretation of sensor measurements. Much research has to be performed before it is understood how health messaging for short periods of data collections should be communicated.

This Section

- Discusses how to identify the sensor technology best suited for your intended application
- Outlines the key questions to consider when purchasing a sensing device

3. Before You Purchase a Sensor

It is important to “ask questions” before you begin collecting data. This will help you have a clear concept of what it is you are hoping to accomplish via the collection of air pollution data prior to beginning a monitoring project. It is also an important step to take when purchasing an air sensing device. Defining the questions you hope to answer will help identify the pollutant of interest, the field conditions you are likely to encounter, the duration of data collection, and the type of measurements needed (i.e. short-term, mobile measurements vs. long-term, stationary measurements) and the quality of these measurements. All of these data collection characteristics will determine the sensing equipment that is best suited for your data collection purposes.

Here are a few examples of the types of well-defined questions that users and developers should ask to help in the identification of an appropriate sensing device. These examples will be used to illustrate the concepts and choices that are important in using sensors.

a. How can I teach my students about air quality and integrate hands-on data collection into the lesson plan?
b. What is my exposure to air pollution during my usual walking route?
c. Is the nearby oil and/or gas facility creating an air pollution concern in my neighborhood?

3.1 What to Look for in a Sensor

There are several things to think about before purchasing a sensor. First and foremost is to determine a target pollutant. This will guide each of your subsequent decisions, and ultimately lead you to the most appropriate types of sensors for your application. Also important to consider are device specifications like detection range and detection limit, precision and bias, calibration procedures, and others, each of which is discussed below, and in greater detail in Appendix C.

Selecting a target pollutant: What pollutants do you need your sensor to measure? The answer to this will depend on the question you have decided to ask. Be sure to consult Table 2-2, which identifies common sources of various pollutants, for guidance. It is important to remember that your decision will be further influenced by what sensors are available within your price range.

We have used questions a, b, and c from above to provide three examples of how to choose a target pollutant. While this list does not address all potential applications/pollutants of interest, it does illustrate how the design of a project can influence choices about key pollutants, and the sensors to measure them.

a. Education project: Projects like this are primarily concerned with building a basic understanding of the pollutants in question. Accordingly, you may choose to use a low-cost sensor that can detect a common pollutant. Ozone is one example of a common outdoor pollutant that can be detected by inexpensive sensors. If ozone is an air pollutant of concern in your area, this might be a good choice. A good way to tell whether ozone is common in your area is to visit the links provided at http://www.epa.gov/airquality/greenbook/hindex.html. If you are in or near a "nonattainment area" then you can expect ozone to be present in higher levels (note: these levels will vary seasonally – visit http://www.epa.gov/air/ozonepollution/ for more information on ground-level ozone and ozone pollution).

b. Daily walk: If you walk near roads or highways, you may choose to measure NO_2, or particulate matter (PM), both of which often indicate air pollution emissions from traffic. For more information on NO_2 and PM, visit http://www.epa.gov/air/nitrogenoxides/ and http://www.epa.gov/airquality/particlepollution/.

c. Nearby oil and/or gas facility: Emissions from oil and gas facilities typically include volatile organic compounds (VOCs), particularly benzene, so this may be a good choice for measurement. It is important to note that sensors selective enough to detect for individual VOCs (i.e. benzene) are often quite expensive, so choosing one that measures VOCs generally can be a low-cost alternative. Such a sensor will respond to a wide variety of VOCs as a general indicator of their presence.

Consider detection range and detection limit: Environmental pollutants can often be present in very low concentrations, particularly when measurements are being made far from the source of the pollution. A sensor will be most useful when it is able to measure a target pollutant over the full range of concentrations commonly found in the atmosphere (consult Table 2-2 under "Range to Expect" for each pollutant). Depending on how close you are to a pollution source, the ability of the sensor to be accurate at either very low or very high concentrations must be understood before you collect any measurements.

To ensure that concentrations at the low end (see ranges in Table 2-2) do not go undetected, you will need to determine the detection limit of the sensor you are looking to purchase. The detection limit is the lowest concentration of a pollutant in the environment that a sensor can detect, and may or may not be provided by the manufacturer.

For example, carbon monoxide (CO) in outdoor air often occurs at background levels in the range of 40-200 parts per billion (as shown in Table 2-2). The carbon monoxide detector sold for use in personal residences can detect levels above ~75 parts per million, which is appropriate for its purpose, but not sensitive enough for measuring outdoor CO for most environmental studies. For many environmental uses, very sensitive detectors are needed that measure CO concentrations well under 5 parts per million (ppm). Depending on the pollutant, ambient levels may be somewhat higher in urban areas, so sensors with detection limits above the background concentrations shown in Table 2-2 may still be useful in some settings. Similar pollutant ranges and needed sensitivity issues exist with all monitoring devices. You will need to either establish these characteristics with the manufacturer or evaluate them yourself as part of your using them.

Consider precision and bias: Precision and bias are terms that refer to the **accuracy** of a sensor measurement (see Figure 3-1). Accuracy is the overall agreement of a sensor's measurement to the true value. Precision refers to how well the sensor reproduces the measurement of a pollutant under identical circumstances. Bias refers to measurement error; for example, a sensor may always measure a little higher or lower than the true concentration. Before purchasing a sensor, you should consult the manufacturer's specifications about reported precision and bias for the sensor. In addition, the user should then conduct their own precision and bias measurements as defined in Appendix C to further qualify the value of the data they are collecting. Table 5-1 identifies acceptable ranges of precision and bias for various sensor applications.

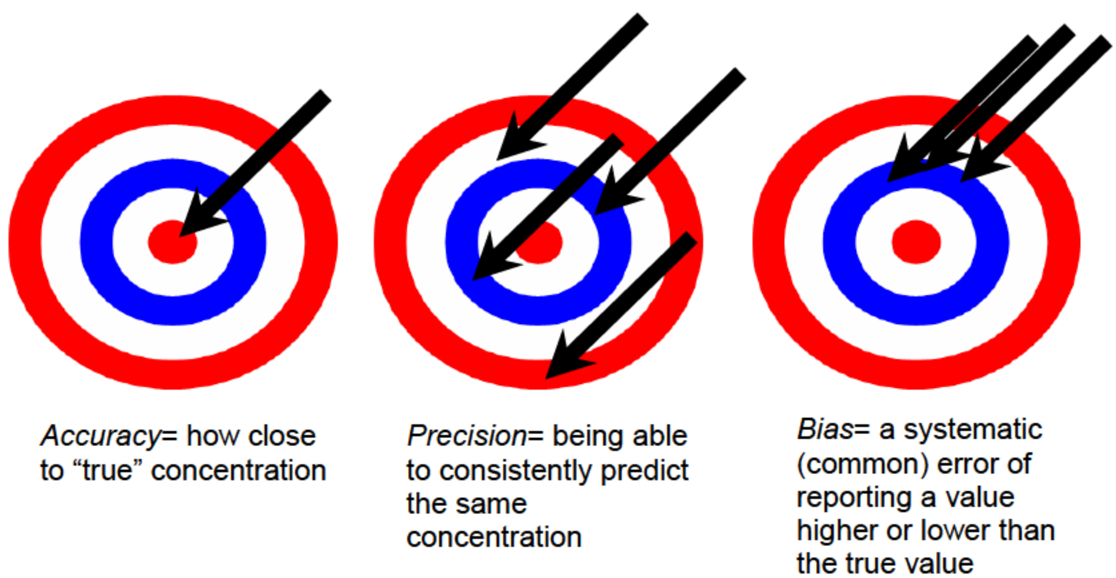

Figure 3-1. Graphics illustrating accuracy, precision, and bias

You should also be aware that accuracy, precision, and bias of a sensor can change over time. For example, exposure to warm temperatures or humid air may lead to a gradual increase in bias (also known as drift). The sensor may experience interference from other chemicals in the atmosphere that could lead to erroneous concentration estimates. Some sensors may come with an "expiration date" after which its measurements are no longer likely to be accurate. For more detailed information on precision, bias, and related concepts, please consult Appendix C.

Identify calibration requirements: Calibration is the process of checking and adjusting an instrument's measurements to ensure that it is reporting accurate data[25]. Calibration compares the response of the instrument to a known reference value. Calibration is important because sensor performance can change over time. If at all possible, sensors should be calibrated for their response before, during, and after a set of data collections. Guidance on this issue is provided in Appendix C. Before you purchase a sensor, find out if it has been calibrated by the manufacturer. Also be sure to check the user manual for information on specific instructions concerning how to calibrate your sensor, including how long the calibration will last once the sensor is being used.

Understand Response Time. A sensor may be quick or slow to measure a pollutant in the air. A sensor that responds quickly may be useful for mobile monitoring and for observing very rapid changes in pollutant concentrations. A sensor that responds slowly may be more suited to stationary monitoring of pollutants that vary in concentration gradually. Your specific data collection goals and intentions will determine which type of sensor is best. It is desirable for a sensor to respond in less than 1 minute if it is to be used in any mode other than stationary monitoring.

Verify durability and quality of construction: Durability is referring to a sensor's ability to endure wear and tear and continue to perform. Sensors are likely to experience such effects during normal use. For example, sensors that are carried by the user or are used for mobile monitoring on vehicles might be jostled, shaken, hit against other objects, or dropped. All sensors measuring outdoor air quality are likely to be exposed to variable weather conditions such as heat, moisture, and dust. The sensor manufacturer should be able to describe the general durability of the device. Even so, they are often not able to describe specifics about how many times you can drop the device or other events before it will fail.

Packaging: Packaging refers to the material used to contain the sensor system components. Packaging can be used to provide protection from water, light, temperature variations (by adding heaters or cooling fans), and electromagnetic noise. However, the air sampled by sensors often comes into contact with sensor packaging. Because of this contact, packaging may interfere with or actually contribute to pollutant concentration levels. Sensors with strong, waterproof, non-reactive packaging will be more durable over time. Reactive materials might include certain types of plastics and coatings that might react with the pollutant of interest or even release the pollutant, interfering with collecting data accurately.

Consider sensor usability: Usability refers to the ease of use of a sensor – is it straight-forward to operate? Air sensors are used by a wide variety of people, ranging from those with no formal training in air quality science to researchers who have many years of advanced training and expertise. Intuitive and easy-to-use sensors will be more attractive for projects that rely on community involvement and citizen scientists, while sensors that provide more detailed information may be preferable for more advanced users.

Other important considerations include how the sensor is powered; if the sensor relies on a battery, how long is the battery life? Is it a rechargeable or replaceable battery pack? Also consider how the data is stored, processed and transmitted – is the data wirelessly transmitted?

[25] http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20001QWV.txt

Or is manual processing required? Experience tells us that establishing wireless communication between a sensor and a web service is not always easy and may even depend on the type of cellular provider for a given geographical area.

Cost: The cost of sensor technology may vary greatly depending on the pollutant to be measured and the degree of accuracy and sensitivity one needs[26]. In general terms, costs often range from $100 to $2500 for what might be considered “consumer-based” air quality sensors. Even within a given pollutant, the cost range might be very large depending on the features of the device.

Potential red flags: Just as the characteristics above can help find a sensor that is appropriate for your specific applications, their absence can be cause for caution. Next generation air monitoring technology is part of an emerging market, and as such there is likely to be a wide range in the quality and reliability of available devices. Some sensor devices have been tested for measurement performance, durability, and usability, but many others have not. While the EPA is beginning to test some currently available sensor technologies[27], as of the writing of this manual there is no formal process for verification. We suggest that you use the information provided here to carefully review a sensor, including its user manual, before purchasing. When investigating a sensor for purchase, it is also important to consider demonstrated performance, measurement repeatability, and feedback from past users.

Table 3-1 provides examples of a few commercially available portable, low-cost air pollution sensors.

Table 3-2 provides examples of performance characteristics of commercially available and emerging sensors for continuous measurements of PM mass and physical properties. There are many lower cost sensors now available. The examples provided here are reported solely to share the types of sensors being developed and some of their stated capabilities. A recent report has attempted to define the current market status of a wide variety of high performance to citizen science type air quality sensors[27]. Sensor users need to carefully consider all available information in selecting the right sensor for any specific purpose.

[26] Mobile Sensors and Application for Air Pollutants (NTIS PB 2014 105955), 2014. EPA/600/R-14/051.
[27] More information on this initiative can be found at http://www.epa.gov/airscience/air-sensor.htm

Table 3-1. Performance characteristics of a few commercially available portable, low-cost air pollution sensors.

Analyzer	Sensor Technology	Range	Accuracy	Precision	Environmental Limits	Weight (kg)	Response Time (s)	Price USD
CO (8 h: 9 ppm; 1 h: 35 ppm**)**								
Langan DataBear, I T15d	Electrochemical Cell	2–200 ppm	0.5 ppm	0.5 ppm	23 to 40 °C	0.43	≥ 1	1.5K
Aeroqual Series 500	Metal Oxide Semiconductor (MOS)	2-100 ppm	<±2 from 0-20 ppm; <±10% from 20-100 ppm	0.1 ppm	0-40 °C, 5 to 95% RH	< 0.46	< 150	1.5K
NO_2 (1 h: 100 ppb; annual average: 53 ppb)								
Aeroqual Series 500	MOS	0.01-200 ppm	<±0.01 from 0-0.1 ppm; <±10% from 0.1-0.2 ppm	1 ppb	0 to 40 °C, 30 to 70% RH	< 0.46	<180	2K
O_3 (8 h: 75 ppb)								
2B Technologies, 202; FEM EQOA-0410-190	UV absorption	1.5 ppb to 250 ppm	1.5 ppb or 2%	0.1 ppb	0 to 50 °C	0.70	10	5K
Aeroqual Series 500L	MOS	8-500 ppb	8 ppb	1 ppb	-5 to 50 °C, 5 to 95% RH	< 0.46	< 60	2K

Analyzer	Sensor Technology	Range	Accuracy	Precision	Environmental Limits	Weight (kg)	Response Time (s)	Price USD
OMC-1108	Electrochemical Cell	0.01 to 10 ppm	±10%	10 ppb	0 to 40 °C, 0 to 80% RH	0.5	< 70	1.2K

Adapted from Snyder et al[28].

Table 3-2. Performance characteristics of commercially available and emerging sensors for continuous measurements of PM mass and physical properties.

Reference Sampler / Sensor	Measurement Principle	Manufacturer	Accuracy	Precision	Limit of Detection ($\mu g/m^3$) or Lower Particle Size Detected (µm)	More Information** Weight (kg) and ~Cost ($, when available) as of May 2014
831 Aerosol Mass Monitor	Light scattering; Mass concentration	MetOne Instruments	±10% to calibration aerosol	-[b]	0.5 µm	Range: 0-1,000 $\mu g/m^3$; 0.8 kg; <$2,000
Personal DataRAM, Model pDR-1500	Light Scattering; Mass concentration	Thermo Scientific	±5% of reading ± precision	±0.2% of reading or ±0.5 $\mu g/m^3$ 60-s avg	0.1 µm	Size Range: 0.1–10 µm; Conc Range: 1 to $4x10^5$ $\mu g/m^3$ Precision (2σ); 10-s avg; 1.2 kg; $5500 with PM2.5 and PM10 cyclones

[28] The Changing Paradigm of Air Pollution Monitoring. Emily G. Snyder, Timothy H. Watkins, Paul A. Solomon, Eben D. Thoma, Ronald W. Williams, Gayle S. W. Hagler, David Shelow, David A. Hindin, Vasu J. Kilaru, and Peter W. Preuss. *Environmental Science & Technology* 2013 *47* (20), 11369-11377

Reference Sampler / Sensor	Measurement Principle	Manufacturer	Accuracy	Precision	Limit of Detection ($\mu g/m^3$) or Lower Particle Size Detected (µm)	More Information** Weight (kg) and ~Cost ($, when available) as of May 2014
DC1100 Air Quality Monitor	Light scattering; Laser particle counter	Dylos Corp.	-[b]	±15%, collocated**	0.5 µm	Size ranges: Pro: >0.5 µm, >2.5 µm or Household: >1 µm, >5 µm, difference between size ranges equals reported counts; Linear up to ~10^6 pt/mL with <10% coincidence**; ~0.4 kg;< $300
microAeth® Model AE51	Light absorption, 880 nm	AethLabs; Black Carbon	no standard for comparison	±0.1 µg BC/m^3 60-s avg**	<0.16 $\mu g/m^3$, 2.5 mL/s, 60-s avg	Precision at 2.5 mL/s flow rate; Range: 1-1000 µg BC/m^3 Resolution 1 ng BC/m^3; 0.3 kg; $6,000

[a]Conversion from light scattering, particle number or size distribution, requires estimates of particle density and shape factors; [b]No data. Performance capabilities are from manufacturers' datasheets except where noted with a **. Text in bold type represents a typical fixed-site higher-cost monitor for comparison purposes only to the sensors that follow in that category. Adapted from Snyder et al[29].

The list provided in Tables 3-1 and 3-2 are not intended as recommended sensors. These represent some whose performance has been better established at the time this report was developed. The list of commercially-available sensors is expanding. The U.S. EPA has plans of sharing reports in the future (2014-2015) where sensors that have undergone specific laboratory and/or real-world evaluations shall be described. Even so, sensor users should perform their own market surveys to determine which sensors might best fit their budget and data collection needs.

[29] The Changing Paradigm of Air Pollution Monitoring. Emily G. Snyder, Timothy H. Watkins, Paul A. Solomon, Eben D. Thoma, Ronald W. Williams, Gayle S. W. Hagler, David Shelow, David A. Hindin, Vasu J. Kilaru, and Peter W. Preuss. *Environmental Science & Technology* 2013 *47* (20), 11369-11377

Designing a Real-World Monitoring Initiative: The Village Green Project

EPA's Village Green Project was initiated in an effort to develop a self-powered, low-maintenance monitoring system to measure air quality in Durham, NC. The project, intended as a community research and educational effort, incorporates a series of sensors into a public park bench structure. While these sensors collect and stream local air quality and weather data, people can interact with the system to learn more about air pollutants and pollution trends. The prototype system, installed outside of the Durham County Library South Regional Branch, has collected 5,664 hours of data since June 20, 2013, all of which is now available on the project website (www.villagegreen.epa.gov).

Before the Village Green Project could launch and data could be made available, the project team needed to identify the most appropriate sensor technology for this particular application. Team members worked together to identify the research question, and then used this question to guide the identification of constraints and the selection of instrumentation. This real-world example helps illustrate the design and selection process that sensor users should go through before purchasing a device and collecting data.

Research Question: How can we measure outdoor air quality in a community setting with a minimal footprint, high quality data, and in support of community engagement?

Instrumentation Constraints:

- ✓ Efficient energy usage to support a self-powered system
- ✓ Long-term accuracy and precision of measurements without significant infrastructure to maintain (avoid costly auto-calibration systems and power-hungry heating or cooling)
- ✓ Real-time active monitoring technology with capability to directly output measurements to a database (enable public access to and interaction with real-time data)
- ✓ Detection sensitivity at background to urban levels (capture a range that accurately reflected local air quality trends)
- ✓ Data provided by the instrument to monitor performance
- ✓ Past record of proven performance in similar measurement environments (ensure ability of sensor to withstand expected monitoring conditions)

Based on the above criteria, only a few instruments were available at the time of selection (Fall 2011). The research team decided to utilize a light-scattering method to measure particulate matter (PM), which showed promise in correlations with higher-cost, mass-based PM measurements. This instrument met the criteria for being low power and low maintenance, and was sensitive down to very low concentrations. The other instrument applied to the monitoring set-up was an ozone monitor that measures using ultraviolet light-absorbance. Similarly to the PM instrument, the ozone monitor is low power, low maintenance, has long-term stability, and is sensitive at ambient concentrations. The constraints imposed by the research question led the project team to implement higher cost instruments (~$5,000 USD) for this particular application than would be used by most people, but which were ideal for the intended project.

3.2 What to Look for in a User Manual

It is also important that the sensor technology being purchased has a complete and informative user guidebook/manual. This manual will serve as your roadmap of operation, outlining the key operation requirements and characteristics of your monitoring device. Look for effective manuals to include:

- General operation (i.e. how to turn on and off, how to charge or change batteries);
- How to store and recover data;
- Conditions of operation;
- Sensor expiration date (if there is one);
- Directions for calibration (if the sensor has that capability);
- Expected performance (precision and bias);
- Maintenance requirements;
- Response time (how quickly does the sensor respond to changing conditions);
- Target pollutants;
- Support information (i.e. company representative, customer support number);
- Technical specifications (i.e. type of sensor used, data storage capabilities);
- Known interferences;
- Demonstrations of sensor performance in real-world applications (ideally in the form of scientific articles reporting on sensor tests)

Sensors that come without a user manual, or with a user manual that is incomplete, may be more difficult to use and maintain. It is strongly advised that you read through or inquire about a user manual before purchasing a particular technology.

This Section

- Describes how to plan your data collection, review, and analysis
- Lists basic steps for collecting useful data

4. How to Collect Useful Data Using Air Sensors

The five basic steps to collecting useful data with air sensors are (1) ask a question, (2) develop an approach, (3) determine sensor location, (4) collect measurements, and (5) understand and communicate results. This section, while not meant to be a comprehensive guide, briefly describes these five steps, which apply to all sensor applications.

1. **Ask a Question.** It is important to take the time to clearly establish and document what question you would like to answer before you begin developing your plan to collect measurements. A simple question, such as "Are ozone concentrations higher in the afternoon than in the morning in my neighborhood?" can help you get started.
2. **Develop an Approach.** Once you have established the question you would like to answer, it is time to plan how the measurements will be made. Think about these issues:
   - The dimension of the problem. Section 2.3 and Appendix B provide some overview of how pollutants may change over time and/or location.
   - The who, what, where, when, and how. Who will take the measurements? What measurements are needed? Where and when should measurements be taken? For how long should measurements be conducted, and how should samples be taken?
   - The number and quality of sensors needed. For example, will your question be better answered by one powerful sensor (i.e., very accurate) or multiple inexpensive sensors collecting less accurate data.
   - The resources (e.g., funding, knowledge) and labor required.
   - How the data will be collected and stored.
   - How you will ensure your data are of good quality, and the degree of quality you need. Section 5 and Appendix C provide further guidance on this topic.
   - What additional data (e.g., meteorology, other pollutants, site information) are needed to answer your question? See Appendix B for more information.
   - How you might address the potential questions that other parties may ask, a sampling of which is provided in Appendix A. You should be able to answer the questions in this list if you wish to communicate the value of the data you have collected to others.
3. **Determine Sensor Location.** Careful planning of your measurement approach is an incredibly valuable process that can help minimize complications later. Developing a specific monitoring plan will also allow you to share your ideas and project design with others before you have invested time and/or money. Whenever possible, share your plan with those you hope to communicate with about your future findings, and/or with experts in the field who are willing to give you constructive feedback. Such information

sources might include local and state air quality officials, university researchers, and trained community environmentalists. This may help you identify potential problems at an early stage. Such an effort is worthwhile, because it is likely that you will need some or all of this information to answer questions about your measurements when presenting your results. To ensure these results are as accurate as possible, a sensor or instrument should be placed in a location where it can measure the atmosphere or source of interest with minimal interference. A well-placed site would yield data that are representative of the area being monitored.

Why it matters: Air pollution concentrations can be considerably affected by local sources, buildings and other structures, among other factors. You will want to consider potential effects when you choose a monitoring location. If emissions from sources close to the site are not of interest, then the site may not be suitable for monitoring. The data will be most useful if you can measure the pollutant of interest with little impact from other sources at your site. Here are some important considerations:

- Allow free air flow to the sensor by making sure it is far enough away from the ground (1-2 meters above the surface) and away from building surfaces, if possible (ideally at least 1 meter away).
- Avoid local pollutant emission sources if you are trying to measure more general community levels of pollutants.
- Avoid sources of gases that can react with your pollutant of interest (e.g. ozone is depleted very quickly by certain organic compounds, as well by nitric oxide from tail pipes) (see Table 2.1).
- The inlets to personal exposure monitors must have access to the air the person is inhaling. For example, a personal exposure sensor will not make representative measurements if kept in a purse or pocket. Inlets for personal samplers can be close to your body or clothing as long as they are sampling air *outside* of your clothes. PM is a special case, since clothing is a source of PM.
- Taking some preliminary measurements can help identify a good monitoring location.

Examples of Sensor Placement Considerations

Location of sources relative to the pollutant of interest. Some pollutants may have higher concentrations closer to a particular source, while others may not. Let's say you want to measure how a freeway influences ozone and particle (PM) concentrations. Ozone concentrations may be depleted next to a roadway because it reacts with freshly emitted nitric oxide (NO). PM is likely to be highest directly adjacent to the roadway, and then decrease with distance. Therefore, you could choose to monitor for both pollutants close to the road, and also some distance downwind of the roadway, to determine the change in concentrations that occurs near the roadway.

Location of the sensor relative to the exposed population. If your study objective is to measure the *impact* of an industrial source on the pollutant concentrations in a community, the sensor might be placed in a neighborhood. In contrast, if you want to measure the *emissions* each day from the same industrial facility, the sensor might be used very close to the source and moved around to map the pollutant plume.

4. **Collect Measurements.** With your measurement approach clearly defined and your sensor properly located, it is time to collect your data. This is not as easy as just turning on your sensor and collecting measurements; you will need some additional preparation before and during data collection. Preparations may include:

   – *Quality Control* – It is advisable that you calibrate a sensor before collecting measurements, and at periodic intervals during measurement collection, to test instrument response to changes in concentrations. A calibration procedure checks an instrument's response by comparing them to a standard or reference value[30]. Sensor calibration is vital for producing accurate data. Ideally, calibrations are carried out under the same conditions (temperature and humidity ranges, concentration ranges, background air, etc.) as those in which the instrument will collect measurements, because many sensors are strongly influenced by these conditions. Sensor manuals often include information on how to calibrate a device (if necessary – some devices can be purchased pre-calibrated).

     Likewise, sensors should be evaluated for precision by testing them multiple times with "clean" air containing none of the pollutant. Such testing is then followed up by testing the unit multiple times with an air source having a known concentration of the pollutant. Data at the "zero" and higher concentration will allow you to determine how well the sensor repeats itself under various conditions.

     Bias, an error in the measurement that is repeatable, can be determined by taking multiple measurements with the sensor and comparing these data with the "true" concentration. The true concentration can be established by a reference monitor located in close proximity to the sensor. For more information on these concepts, refer to Appendix C.

   – *Sensor Maintenance* – Some actions may be required to maintain sensor performance over the measurement period. Sensor maintenance processes include regularly cleaning internal surfaces (especially optics) to prevent the buildup of bugs or dust, replacing filters and/or batteries, and examining site features to ensure that no significant changes to the landscape have occurred. Sensor maintenance processes over both the short- and long-term are discussed in further detail in Section 6 and Appendix C**.**

   – *Data Review* – A data review is a technical evaluation of the data collected by a monitoring device[31]. It is a good idea to evaluate the quality of your data during the collection phase to identify and correct potential problems that may arise. In order to do this, analyze data to look for seasonal, day/night, or weekday/weekend patterns. An absence of expected patterns may indicate a problem with your sensor or with your measurement approach.

   – *Data validation* – Data validation is the process of evaluating collected data against established acceptance criteria to determine data quality and usability[31]. As you are collecting data, it is important to visually screen for odd patterns, decreases in overall response, and other unusual features. If you wait until your study is complete, it will

[30] http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20001QWV.txt
[31] http://www.epa.gov/esd/factsheets/data-auditing.pdf

be too late to fix these issues, which tend to produce data that look too regular or change too abruptly to be caused by natural atmospheric phenomena. Some specific problems which may occur during data collection include:

- **Interferences** - factors that hinder, obstruct, or impede the ability of a sensor to make accurate measurements. Interferences may have a positive or negative effect on sensor response, and can include anything from pollutants or other chemical compounds that are not of interest to weather conditions and dirt/dust/insects. It is possible for a sensor to respond to several different interferences simultaneously. Manufacturers usually disclose pollutants and weather conditions that may impact sensor performance, but may not describe how severely the sensor will be affected. Before using a sensor to monitor air quality, consider possible sensor interferences, test for them, and minimize them if possible.
- **Drift** – refers to a gradual change in a sensor's response characteristics over time. Instrument drift may lead you to wrongly conclude that concentrations have increased or decreased over time. Drift can be positive or negative, and it may occur due to a variety of reasons. One way to reduce drift is to calibrate the sensor frequently so that the instrument only drifts a small amount between each recalibration. The frequency of calibration needed will depend on how much drift occurs.

5. **Analyze, Interpret, and Communicate Your Results.** The way you present your results to your audience is critical to successfully sharing your understanding of the data and achieving the objectives of sensor-based air quality data collections. Common ways of visualizing data are: graphs of pollutant concentrations over time to show daily, weekly, seasonal, or yearly variation in concentrations; charts of wind direction and/or pollution to identify sources, and maps plotting data from several sensors to illustrate patterns in concentrations[32]. Generally, simply showing the measurements that you have collected will not be sufficient; your audience will want to know about all the steps that you took to ensure data quality:

   – Quality Assurance – Adequate planning to ensure that sensor design and use met the performance requirements of your specific application. Depending on your intended use of the data you collect, you might consider data quality assurance at various levels (Section 5.1). For instance, data intended for a direct comparison with State or Federal monitoring would require significantly more quality assurance than a general survey of pollutant concentrations for informational purposes only (such as an educational event for a grammar school).

   – Quality Control – Sensor calibrations, precisions and bias checks, maintenance, and data audits required for your application during data collection to identify and correct potential issues such as sensor degradation, problems with sensor location, etc.

[32] See Appendix B of the EPA's *Data Quality Assessment: A Reviewer's Guide (EPA QA/G-9R)*, available at www.epa.gov/QUALITY/qs-docs/g9r-final.pdf, for some helpful tips on data displays.

- Quality Assessment – Determination of the quality of your measurements and sufficient analysis of the data prior to reaching final conclusions.

Regardless of whether you present your results as a written report, a presentation, or in conversation, you should be able to describe your approach, the measurements you made, the quality checks you had in place (calibrations, etc.), and your interpretation of the data. If any one of these components in missing or not well executed, the usefulness of your data will be compromised.

Keep in mind that using sensors to answer a question about air quality is often an iterative step by step process. You may find that your measurements do not satisfactorily answer your question, or you may find yourself with many more questions after analyzing your data. Reevaluate your approach and repeat the steps described above as needed.

5. Sensor Performance Guidance

This Section

- Helps you select sensor performance metrics appropriate for your application
- Describes different types of applications for sensors
- Presents a table of performance metrics

The performance of an air sensor or instrument describes its overall ability to measure air pollution. This section provides initial guidelines on how well a sensor or instrument needs to perform in order to be used for different types of air pollution applications. Specifically, we define each application, provide performance metrics for a range of different applications, and provide several real-world examples.

5.1 Application Areas

We have defined five application areas of interest to sensor users. These are: I) Information and Education, II) Hotspot Identification and Characterization, III) Supplementary Network Monitoring, IV) Personal Exposure Monitoring, and V) Regulatory Monitoring, as discussed below. Several real-world examples from organizations using sensors are provided to illustrate these application areas. For your reference, Appendix C provides a detailed discussion of a number of technical considerations, including how to find the precision and bias of a specific sensing device. It must be stated that no low cost sensors meet the Regulatory Monitoring requirements and the discussion here is for informational purposes only.

Tier I. Education and Information. Educational applications use sensors as teaching tools. These applications center around informational measurements, which are intended to foster informal and qualitative awareness. For example, an instrument might indicate the presence or absence of a pollutant by a signal such as a light going on or off. Or, a device may use qualitative indicators, such as colors, to communicate a general sense of air quality. Such measurements can be used for *relative* comparisons between air pollution levels in two locations or at different times, rather than for measurement of *absolute* levels. Measurements like these may help address questions such as: Is air pollution on my daily commute to work higher or lower than at home? Is air pollution higher today compared to yesterday? Where would it be best for me to run or bike today? Sometimes these sensors may not report air quality in traditional concentration units. However, users may still find measurements made by these unitless scales or colors to be useful for making relative comparisons.

The uncertainty in these types of measurements is quite large. The expectation would be that the air pollution sensor is directionally consistent with pollutant trends; for example, a light might consistently turn on if a PM concentration is 50-100 $\mu g/m^3$ or higher, and consistently turn off if measurements are below this threshold. Even if the “estimated” concentration is appreciably higher or lower than the “true” concentration when using such a device and results in an accuracy error of 50% (e.g. 10 ppb versus 15 ppb), the device might still be useful in educating others where data quality needs are less important.

Sensor technology and sensor use fits within the Next Generation Science Standards (NGSS) - new K-12 science standards that work provide students with an internationally benchmarked science education[33]. The use of sensor technology in an education setting can also help advance science, technology, engineering and mathematics (STEM) learning at various grade levels. Exposing students to STEM education and hands-on science projects (i.e. the development and deployment of air pollution sensors) can improve classroom learning and help support the President's goal to provide students at every level with the skills they need to excel in the fields of science, technology, engineering and math[34].

Tier II. Hotspot Identification and Characterization typically uses fixed location and/or mobile sensor systems to map pollutants and determine emission sources. For example, this can be done by clustering a network of sensors downwind of an industrial facility or shipping port; placing a network of near-road sensors along an urban interstate freeway; or placing sensors in a vehicle for industrial fence line surveys or on an aircraft that flies in and out of a power plant emissions plume. In most cases, the sensors will be making measurements close to the emission location, where pollutant concentrations are usually high. One example of sophisticated hot spot identification is the U.S. EPA's Geospatial Measurements of Air Pollution (GMAP) monitoring vehicle (www.epa.gov/nrmrl/appcd/emissions/sec_gmap.html). For Tier II applications, a bias and precision of ±30% might be reasonable.

Tier III. Supplementary Network Monitoring (also referred to as "exploratory monitoring") is the use of air sensor systems to complement an existing network of air quality monitors. This is done by supplementing the regulatory network with many lower-cost devices, filling in spatial gaps. These additional sensors may be at a permanent fixed location, or on mobile platforms, depending on network objectives. The data from supplemental monitoring may not be sufficient for regulatory purposes, but may help you identify potential pollution sources of interest. A selection of state and regional officials said in interviews that if they were presented with community group data that had a precision and bias of 20% or better, they would be willing to investigate the findings further (provided the project design and execution seemed reasonable). This general consensus must not be considered as representative of all state and federal air quality officials or their opinions on this subject. Likewise, these descriptions of precision and bias error ranges are application dependent and probably highly conditional to the pollutant being monitored and the circumstances involving the data collections. European guidance suggests a precision and bias range of 30-50% might be applicable. Note that there currently exists no U.S.-based defined role for supplemental monitoring requirements and the discussion here is solely for informational purposes.

[33] http://www.nextgenscience.org/
[34] http://www.whitehouse.gov/issues/education/k-12/educate-innovate

Education Application: AirCasting Queens Vocational & Technical High School

In 2012, HabitatMap received an Environmental Justice Community Impact Grant from the New York State Department of Environmental Conservation to develop and teach a course on air quality monitoring at the Queens Vocational & Technical High School (QVT) in New York City. The course objectives were: (1) Equip students with the skills, knowledge, and tools to record, analyze, interpret, and communicate air quality information; (2) furnish students with hands-on learning experiences that encourage them to engage with their environment, participate in community life, and understand why science, technology, engineering, and mathematics are important in the context of solving real-world problems; and (3) provide the public and policymakers with meaningful and accessible air quality information that would lead to more informed decision-making and improved air quality.

26 students from QVT participated in the course and built their own air monitors using open-source information and instructions from AirCasting.org. The students learned the basics of air quality, constructed their own PM sensors using parts that are widely available from online vendors, and used a 3D printer to create enclosures to house and protect the electronics assembly. The total cost of electronics for each air monitor was approximately $120.

The students toured the neighborhood around their school and recorded thousands of particulate matter measurements and dozens of observations related to air pollution hot spots and air pollution incidences (e.g., idling vehicles, visible smokestack emissions, black exhaust from diesel trucks). They presented their findings to their peers, members of the Newtown Creek Alliance, and staff from the New York State Department of Environmental Conservation. Their aggregated measurements are available on the AirCasting CrowdMap. Because these devices were not calibrated and the quality of the data was not verified, this fits more in the Education and Information application of showing qualitative data.

By learning how to build air monitors, understand air quality in local context, and use the AirCasting platform to record, map, and share their findings, these QVT students learned how science, technology, engineering, and mathematics can be used to inform the possible solutions to real-world problems.

The map at the right shows student-recorded PM levels throughout Sunnyside, Queens, New York City. Colored points indicate sampling locations, with different colors representing difference levels of air quality:

- Green: below detection limit
- Yellow: low
- Orange: medium
- Red: high

CrowdMap showing all of the combined measurements. http://bit.ly/15d7gbk.

Supplemental Monitoring in the European Union (EU)

The EU directive on "ambient air quality and cleaner air for Europe" provides for the use of "indicative measurements." These measurements can be used to supplement "fixed" (or, "regulatory") measurements to provide information on the spatial variability of pollutant concentrations. These supplementary measurements have less stringent requirements for data quality. The performance requirements for the fixed and indicative measurements are defined below. There are several differences between U.S. and EU efforts:

- The directive 2008/50/EC is a regulatory document, and makes provisions for the use of indicative measurements to supplement fixed measurements in the regulatory process. However, no provision is made for them to be used in isolation for regulatory purposes. Currently, in the U.S., there is no defined role for supplementary sensor measurements in regulatory monitoring, and this document does not provide one; the performance metrics in Table 5-1 are suggestions only.
- The EU performance requirements relate only to the use of indicative measurements to supplement fixed measurements for regulatory purposes. Therefore, while the performance requirements of the indicative measurements vary by pollutant, there are no performance requirements for the other application areas discussed in this document.
- EU performance requirements are listed below (from Table A of Annex I of the directive 2008/50/EC). Note: the EU requirements specify a maximum uncertainty, and do not address precision and bias separately.

Type of Measurement	Maximum Uncertainty Allowable in Pollutant Measurement			
	SO_2, NO_x, CO	Benzene	PM & Lead	Ozone
Regulatory (fixed)	15%	25%	25%	15%
Supplemental (indicative)	25%	30%	50%	30%

EU directive 2008/50/EC can be seen at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF

Tier IV. Personal Exposure Monitoring encompasses any application where a person's exposure to air pollution is monitored, often to evaluate the impact of air pollution on health. This may include measurements taken to protect an individual whose health might be impaired by elevated air pollution, or an epidemiological research study to help understand the effects of air pollution on a group of people. An example of one such effort was the U.S. EPA's Detroit Exposure Research Study (DEARS), where participants were involved in wearing portable sensors to document their exposures (http://www.epa.gov/dears/). Personal exposure studies have historically been research projects where people wear devices that measure air quality as they go about their daily routines. In the future, people may monitor their own exposure to air pollution to help make medical decisions. Personal exposure is currently estimated using EPA's Air Quality Index (AQI), which communicates health risks from air pollution using a color-coded scale. For this application, a bias and precision of 30% or better might be a goal for such air quality monitoring scenarios.

Tier V. Regulatory Monitoring includes monitoring for criteria pollutants to determine if an area is in compliance with the National Ambient Air Quality Standards (see section 1.3 for more information). In the U.S., regulatory monitoring is performed by air quality agencies and governed by the performance requirements specified by the Code of Federal Regulations[35]. Instruments or technologies which are used to comply with requirements for regulatory monitoring must meet the requirements of Federal Reference Methods or Federal Equivalent Methods. Requirements include meeting stringent measurement quality objectives and substantial operational requirements[36], and are therefore considered the "gold standard." In contrast, there are no such written requirements for measurements in Tiers I-IV. No low cost sensors have been approved to collect regulatory monitoring data.

The U.S. EPA also regulates air quality associated with a select number of air toxics. One example of such a pollutant is benzene, an air toxic widely distributed in our environment. Sensor users are encouraged to review (www.epa.gov/ttn/amtic/airtox.html) for specific information on data quality for these pollutants. Often precision error of no more than 15% is required to ensure adequate measurements of these air pollutants.

5.2 Suggested Performance Goals for Each Application

As outlined above, sensor systems have the potential to be used across specific air quality measurement applications, which can range from those requiring relatively high-performing measurements to informal projects with minimal data quality requirements.

Table 5-1 provides information about how well your sensor must perform so that the data you collect will be useful. Which of the tiers above best describes the specific purpose of your monitoring effort? Once you have identified the appropriate tier, consult Table 5-1, which has columns for four performance characteristics. Additional data quality indicators and associated

[35] See 40 CFR Part 50 Appendices L and N, 40 CFR Part 58 Appendix A. Also refer to Appendix D of the *EPA Quality Assurance Handbook for Air Pollution Measurement Systems Volume II*, www.epa.gov/ttnamti1/files/ambient/pm25/qa/QA-Handbook-Vol-II.pdf.
[36] Appendix D of *EPA Quality Assurance Handbook for Air Pollution Measurement Systems Volume II* is a synthesis of the requirements specified in the CFR and guidance provided by members of a working group formed by the EPA.

performance characteristics are required for regulatory monitoring and may be required for other applications requiring higher data quality.

- Bias
- Precision
- Data averaging time
- Data completeness

Bias and precision are discussed above in Section 3 as metrics for assessing the accuracy of sensor**.**

Data averaging time is a key performance metric because precision can be improved when more data from a particular measurement system are averaged together. Data are often averaged, or aggregated, to facilitate comparison to measurements from another instrument, health-based benchmarks, or environmental standards. Data averaging helps improve the quality, usefulness, and manageability of your data. The exact type of averaging will depend on your application and the question you are trying to answer.

Table 5-1 provides appropriate averaging times over which data should be averaged for various uses. For example, if you are interested in observing a pollutant concentration trend over the course of a month, you may want to analyze your data to 1-hour or 24-hour patterns. You will be able to see how the concentrations change, but averaging will reduce the amount of data you are working with to a manageable size. It will also minimize the effects of outliers (those individual data points that stray far from the average). On the other hand, if you would like to identify a pollution hotspot, you may prefer to use a shorter averaging period, such as a few minutes, to capture the precise location of the hotspot. A shorter averaging period would allow you to detect the hotspot in your data as the sensor moved around the area of interest.

Data completeness refers to the amount of data that was actually obtained, compared to the amount that was expected (for example, a sensor operating correctly and providing data for 4 days out of a 5 day monitoring test would have 80% data completeness). See Appendix C for more information on these topics.

Detection limit is another important performance metric to consider, but because detection limit needs can vary between projects it is better to assess requirements on a case-by-case basis (see Section 3 for more details). As discussed in Sections 3 and 4, and Appendix C, a wide range of factors influence sensor performance, including interferences from other gases and particles and methods of operating the sensor.

As shown in Table 5-1, the suggested performance goals are different for each of the five application areas (tiers). Tier V is the highest quality level discussed, representing the regulatory monitoring application. Applications in lower tiers have less stringent performance goals.

The performance goals presented in Table 5-1 were developed based on expert interviews, group meetings and discussions, and peer-reviewed and government literature. These performance goals are an initial guideline that will be refined over time as technology, the community's collective experience, and sensor systems evolve and improve.

Table 5-1. Examples of Suggested Performance Goals for Sensors for 5 Types of Citizen Science Applications in Comparison to Regulatory Monitoring Requirements

Tier	Application Area	Pollutants	Precision and Bias Error	Data Completeness*	Rationale (Tier I-IV)
I	Education and Information	All	<50%	≥ 50%	Measurement error is not as important as simply demonstrating that the pollutant exists in some wide range of concentration.
II	Hotspot Identification and Characterization	All	<30%	≥ 75%	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.
III	Supplemental Monitoring	Criteria pollutants, Air Toxics (incl. VOCs)	<20%	≥ 80%	Supplemental monitoring might have value in potentially providing additional air quality data to complement existing 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.
IV	Personal Exposure	All	<30%	≥ 80%	Many factors can influence personal exposures 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.

Tier	Application Area	Pollutants	Precision and Bias Error	Data Completeness*	Rationale (Tier I-IV)
V	Regulatory Monitoring[37]	O_3 CO, SO_2 NO_2 $PM_{2.5}$, PM_{10}	<7% <10% <15% <10%	≥ 75%	Precise measurements are needed to ensure high quality data is being obtained to meet regulatory requirements

Note: These are guidelines only (Tier I- Tier IV), and are likely to evolve over time as technology continues to develop and the state of the science continues to advance. *The amount of data needed for any air quality purpose is highly specific to that purpose and could range from minutes to even years of data measurements.

[37] Precision, bias, and data completeness requirements in part were taken from Appendix D of the *EPA Quality Assurance Handbook for Air Pollution Measurement Systems Volume II* (May 2013 edition). Refer to 40 CFR Parts 50, 53, 58, and the QA Handbook Volume II for activities/criteria for monitoring network data.

6. Maintaining Your Sensing Device

Air monitoring technology, like most other forms of technology, requires careful care and maintenance to ensure proper functionality and reliable performance. These preventative actions are necessary in both the short- and long-term, and may vary with the specific monitoring technology being utilized. By properly caring for a monitoring device you can reduce errors in data collection, extend the shelf-life of the device, and save money that would otherwise be spent on replacement parts and repair services.

Maintenance Processes

Maintenance processes are the actions required to maintain sensor performance over an extended period of time. Good maintenance processes can help maximize and sustain sensor performance. Typical maintenance processes include regularly:

- Calibrating with pollutant standards and flow meters as described under the *Calibration* section of Appendix C.
- Cleaning internal and external surfaces and components to prevent the buildup of bugs, dust, etc.
- Replacing filters and consumables.
- Replacing the sensor when it has failed or reached its lifespan of service.
- Replacing rechargeable batteries.
- Reviewing (visually inspecting) data for odd patterns, a decrease in overall response, drift in the baseline, and other unusual features. Instrument problems tend to produce data that often look too regular and repeatable, or that change too abruptly, to be due to natural atmospheric phenomena.
- Inspecting sensor placement to ensure that no significant changes have occurred (e.g., tree growth, building changes, etc.).

Developing a set of maintenance processes relevant to your sensor helps the user consider how best to deploy and maintain the sensor. Developing and maintaining a logbook to ensure maintenance occurs at regular intervals is helpful.

Learn more:
http://www.epa.gov/ttn/amtic/contmont.html. See the Standard Operating Procedures for regulatory monitors on this website for examples of maintenance done on $PM_{2.5}$ monitors.

7. Additional Resources

Air Quality

- EPA criteria pollutants: http://www.epa.gov/air/urbanair/
- Criteria pollutants overview and standards: http://www.epa.gov/airtrends/sixpoll.html
- Air pollutant information: http://www.epa.gov/air/airpollutants.html
- Black carbon health effects: http://www.epa.gov/research/airscience/air-blackcarbon.htm
- Carbon dioxide emissions page: http://www.epa.gov/climatechange/ghgemissions/gases/co2.html
- Sources of greenhouse gas emissions: http://www.epa.gov/climatechange/ghgemissions/sources.html
- Air quality trends: http://www.epa.gov/airtrends/aqtrends.html
- Weather effects on trends in ozone pollution: http://www.epa.gov/airtrends/weather.html
- Local area trends for criteria air pollutants: http://www.epa.gov/airtrends/where.html
- Atmospheric science and the formation of pollutants: http://www.epa.gov/airscience/air-atmosphericscience.htm#chemistry
- EPA toxics website: http://www.epa.gov/air/toxicair/newtoxics.html

Sensors

- EPA's Air Sensors 2013 and Next Generation Air Monitoring Workshop Series homepage: https://sites.google.com/site/airsensors2013/final-materials
- EPA Next Generation Air Monitoring website: http://www.epa.gov/research/airscience/air-sensor-research.htm
- A forum for the air sensors community to share and collaborate: http://citizenair.net/
- Citizen science opportunities for monitoring air quality fact sheet: http://www.epa.gov/research/priorities/docs/citizen-science-fact-sheet.pdf

Data Sources

- Multiple links to air quality data sources: http://www.epa.gov/air/airpolldata.html
- Access to real-time air quality maps and forecasts from EPA's AirNow system: http://www.airnow.gov
- AirNow Gateway for obtaining real-time data via files and web services: http://airnowapi.org/
- Access to historical air quality data from EPA's Air Quality System (AQS): http://www.epa.gov/airdata/
- Portal to download detailed AQS data: http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm

Health Effects

- EPA's Air Quality Index: A Guide to Air Quality and Your Health: http://www.epa.gov/airnow/aqi_brochure_08-09.pdf

- EPA's Guide to Particle Pollution and Your Health: http://www.epa.gov/airnow/particle/pm-color.pdf
- EPA's Guide to Ozone and Your Health: http://www.epa.gov/airnow/ozone-c.pdf
- EPA's Risk Assessment for Toxic Air Pollutants: A Citizen's guide: http://www.epa.gov/ttn/atw/3_90_024.html

Other

- General Air Research/Air Science: http://www.epa.gov/research/airscience/
- EPA's "plain English guide" to the Clean Air Act: http://www.epa.gov/air/caa/peg/
- Near roadway research and pollutant effects: http://www.epa.gov/airscience/air-highwayresearch.htm
- Role of vegetation in mitigating air quality impacts of air pollution: http://www.epa.gov/nrmrl/appcd/nearroadway/workshop.html
- Air Pollution Training Institute (APTI) Learning Management System: http://www.apti-learn.net
- CDC Agency for Toxic Substances and Disease Registry (ATSDR) Toxic Substance FAQ (ToxFAQ): http://www.atsdr.cdc.gov/toxfaqs/index.asp
- CDC The NIOSH Pocket Guide to Chemical Hazards: http://www.cdc.gov/niosh/npg/

Appendix A: Potential Questions

If and when you decide to share your data with others, it is likely they will have a number of questions regarding the data you've collected and the techniques you've employed. Below we have tried to provide a list of the types of questions to expect. While this list is by no means exhaustive, it gives a general outline of the information you are likely to be asked for.

Basics

- What do you want to find out or show with your measurements?
- What pollutants did you measure?
- Do you consider this a nuisance or a health hazard? Is this a recurring problem?
- Do you know the normal levels for the pollutant, including seasonal and day/night profiles?
- Do you have Standard Operating Procedures (SOPs) (detailed written instructions so that measurements are taken in a consistent way)?
- Did you receive adequate training in how to operate the device and maintain it?

Monitor

- What instrument/sensor did you use?
- How were the measurements taken?
- When did you make your measurements? (i.e. time of day/night, day of week, season)
- How long was the period during which you collected measurements?
- How did you ensure that quality measurements were collected? (How did you calibrate your sensor? How did you estimate precision and bias?)
- Did you co-locate your sensor near regulatory monitors or other approved measurement systems to evaluate their performance?
- How were samples identified and their identity recorded and tracked as they were transferred to others or analyzed?
- What, if any, additional data were collected? (e.g., wind measurements, site photos, GPS, activity logs, event logs, health info)

Location/Surrounding Environment

- Where were the measurements collected?
- Were there other emission sources near the location you were measuring that could have mixed with the pollutants coming from the source of interest? (e.g., roadways, other industrial facilities, etc.)
- Was anyone, including you, smoking nearby when you collected the measurements?
- Did you take the measurements while in a moving vehicle or were you stationary?
- How were you holding the sensor, or was it attached to a vehicle or stationary object?
- What were the weather conditions?
- Were you indoors or outdoors while taking measurements?

Data Analysis

- How will the data be analyzed? (e.g., compare with meteorological measurements, other site data)
- How will you differentiate the source you are trying to measure from the background?
- Did you average your measurements and if so, how?

Other

- Is this an anonymous report, or will you provide contact information for follow up?
- Did you have any interaction with the people creating the emissions? Have you in the past?

Appendix B: Air Quality Concepts and Characteristics

Table B-1 outlines various concepts and characteristics that provide a good foundation for understanding air pollution. This table expands on the discussion in Section 2.3, and includes an examination of how each concept may influence the development and use of air sensing devices. Concepts defined below are generalizations of those reported in the scientific literature for a variety of pollutants and general air quality discussions (http://www.epa.gov/airquality/).

Table B-1. Air quality topics, discussion, and relevance.

Topic	Discussion	Relevance to Sensor Development/Use
Primary vs. secondary pollutants	Pollutants may be emitted directly by a source (primary pollutants) or may be formed as a product of a chemical reaction in the air (secondary pollutants). Primary pollutants that contribute to the formation of secondary pollutants are also called precursors. Spatial difference in primary pollutants can be large, especially if there are no other nearby sources of the pollutants. Spatial differences may be smaller for secondary pollutants.	Consider whether a pollutant of interest is primary or secondary pollutant to help select a monitoring location. In some cases, it may be easier to determine the source of a primary pollutant than the source of a secondary pollutant.
Short-lived vs. long-lived pollutants	The atmospheric lifetime of a pollutant is the average amount of time the pollutant resides in the atmosphere before it is removed by reacting to form a new molecule or depositing onto a surface. This lifetime varies significantly for each pollutant according to its likelihood of reacting with other species (reactivity) or depositing. Species with longer atmospheric lifetimes tend to be more uniformly distributed in the atmosphere, while concentrations of species with shorter atmospheric lifetimes may be more variable in space and time. Atmospheric lifetime of some chemicals may be affected by seasonal temperatures. Short-lived pollutants that react quickly after they have been emitted may be highly variable in space and time. Long-lived pollutants typically show less variation over distances or time.	Detecting a short-lived pollutant requires a sensor that responds quickly. A slower sensor response may be used for detecting long-lived pollutants, especially if the sensor is not moving.

Topic	Discussion	Relevance to Sensor Development/Use
Local vs. regional vs. global scale	The atmospheric lifetime of a pollutant governs whether a source will affect air quality on a local, regional, or global scale. While some air pollution problems are limited to the local area where pollution is emitted (e.g., 1,3-butadiene, a short-lived pollutant), others are transported and impact air quality across cities or entire regions of the country (e.g., ozone, $PM_{2.5}$). For some pollutants, emissions from everywhere on earth contribute to a global problem (e.g., CO_2).	Knowing the lifetime and emission sources of the pollutant of interest helps you understand whether concentrations are influenced by a local source or distant sources.
Weather (e.g., sunlight, winds, temperature)	Concentrations of pollutants are also controlled by weather, including sunlight, temperature, humidity, clouds, precipitation, and winds. Concentrations can increase more rapidly when winds are stagnant. Higher winds typically dilute pollutant concentrations, but may lead to increased concentrations of other pollutants (such as dust).	Air quality and weather are linked. Weather can affect both air pollution concentrations and sensor performance. Therefore, it is very important that you know how weather conditions can influence your sensor measurements.
Time of day	Some pollutants have strong day/night patterns due to source patterns or meteorological changes.	Sensor performance may vary throughout the day due to changes in source patterns and weather.
Day of week	Concentrations of some pollutants vary according to the activity schedule of the source (e.g., traffic patterns, industrial schedule).	When developing a measurement plan, consider the day-of-week pattern in emissions from the sources you are trying to measure.
Season	Some pollutants display a strong seasonal variation because of differences in emissions patterns, formation processes, and atmospheric longevity. For example, wildfires emit particles, VOCs, and NO_x, and are more prevalent in dry, warm conditions; residential wood burning, however, may be more important in the winter.	Consider the seasonal variation of the pollutant of interest to inform your study design. Sensor systems may need to work in particularly adverse conditions such as extreme heat, humidity, or cold.
Near-source concentrations	Concentrations of primary pollutants are typically highest very close to their emissions source. Concentrations generally decrease rapidly within the first few hundred feet of a source as the pollutants are transported and dispersed.	Consider concentration gradients in your study design. More than one type of sensor (or a sensor system with more than one operational mode) may be needed, depending on the range of concentrations that will be measured.

Topic	Discussion	Relevance to Sensor Development/Use
Multiple, well-distributed sources	When there are many widely distributed sources in an area, such as gasoline stations in an urban environment, concentrations may be very similar across the area.	A network of sensors (upwind, near-source, and downwind) may be needed to identify these sources.
Man-made vs. naturally occurring pollutant sources	Typically, measurements focus on human influenced sources, but there are natural sources such as fires, lightning, windblown dust, and volcanic activity.	Consider all sources of the pollutant of interest when designing your study.
Pollutant transport	The distance a pollutant may be transported is governed by atmospheric chemistry (formation and depletion reactions), weather (air mass movement and precipitation), and topography (mountains and valleys that affect air movement). The longer a pollutant stays in the atmosphere, the farther it can be transported and the harder it becomes to identify its source.	Understanding how pollutants are transported can help you identify the source.

Appendix C: Technical Considerations

The quality of data collected with sensors can vary greatly depending on sensor design and your deployment strategy. You must consider the following factors carefully while planning for, making, and processing measurements if you are to produce quality data and useful results. You should be able to show that the quality of the data you collected is sufficient to meet the performance requirements of the application and of the intended audience.

This section describes several factors to consider in order to collect quality measurements from air sensors, regardless of the intended application. This builds upon the discussion in Section 3.1, which introduces considerations relevant to air sensor users and developers.

C.1 Considerations for Air Sensor Users and Developers

The following considerations cover a broad range of performance-related characteristics. We provide a technical description of each topic and explain its relevance to low-cost sensor applications. This section covers the following factors affecting air quality measurements:

- bias
- precision
- calibration
- detection limit
- response time
- linearity of sensor response
- measurement duration
- measurement frequency
- data aggregation
- selectivity
- interferences
- sensor poisoning and expiration
- concentration range
- drift
- accuracy of timestamp
- climate susceptibility
- data completeness
- response to loss of power

Bias

Bias means an average systematic or persistent distortion of a measurement process that causes errors in one direction[38]. Bias can be thought of as a fixed value that is always added or subtracted from the true value of the pollutant by the sensor (Figure C-1).

[38] http://www.epa.gov/quality/qs-docs/g5-final.pdf.

Why it matters: Biased measurements consistently misrepresent the true concentration of a pollutant, usually by producing data that are either regularly higher or lower than the true value of the pollutant by a fixed amount. Bias is usually caused by a characteristic of the sensor, by a problem with the overall measurement method, or by a persistent mistake that the operator inadvertently makes with each measurement. A bias is considered a determinate error (the cause is known) and may be corrected by recalibrating the sensor, altering the method, or correcting operating procedures.

How to calculate it: There is no one correct method of estimating bias. One example of a bias calculation is as follows:

$$B = \left({}^{C}/_{C_R}\right)\text{-1}$$

where B is the bias, C is the average of the measurements, and C_R is the reference concentration, or true value, of the pollutant. Confidence in a calculated bias generally increases with the number of measurements. Zero bias is ideal, but low values for bias may also be acceptable. The bias may change as a function of environmental conditions (e.g., with temperature and humidity), lifespan of the sensor, or other factors. Therefore, consider checking your sensor for bias routinely, with frequent calibrations and/or inter-comparisons with other sensors. Comparisons with high-performance instruments, or sensors that work by another measurement principle, may be valuable.

Learn more: A more in-depth discussion of bias is presented in the text box below. See also www.epa.gov/ttn/amtic/files/ambient/monitorstrat/precursor/07workshopmeaning.pdf.

Figure C-1 shows a comparison of a true value of NO_2 (blue line) and biased measurements of NO_2 (red line). The consistent offset between the two time series is the bias.

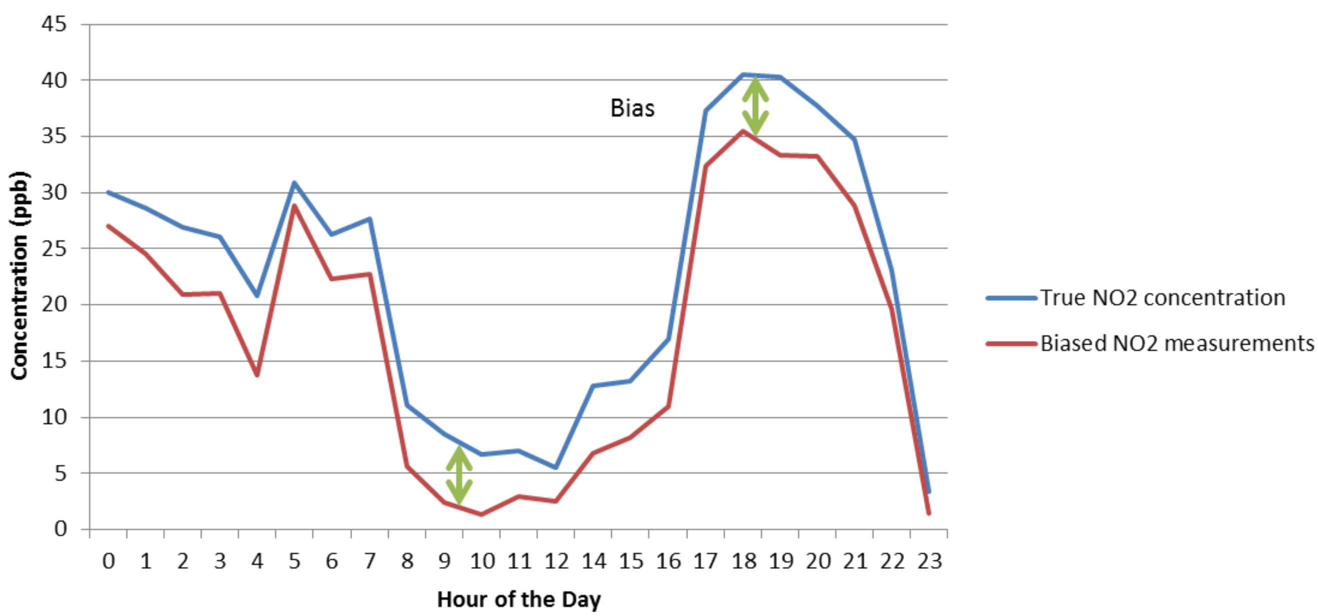

Figure C-1. Comparison of a true value of NO_2 and biased measurements of NO_2.

Precision

Precision measures the agreement among repeated measurements of the same property under identical or substantially similar conditions. The more frequently data are collected over a given period the more confidence one has in the concentration estimate. Precision can be expressed in terms of standard deviation[39]. Precision can be thought of as the scatter introduced into data by random (indeterminate) errors when an instrument attempts to measure the same concentration of a pollutant multiple times.

Why it matters: The precision of a sensor will determine the quantity of data needed to achieve a quality level that is suitable for your needs. The precision of an instrument can be improved by averaging more of the raw data together. For example, if 1-second data are subject to significant random error, the data can be grouped into 5-minute averages so the random errors cancel each other out (Figure C-2). Grouping data often results in fewer individual data points, but the grouped data will be more precise (i.e., a lower standard deviation) and potentially a better representation of the true value of the pollutant, provided the measurements are unbiased. Even so, one must understand how critical the time period is when grouping data. If one wishes to estimate 15-minute data concentrations, grouping data on a one hour basis to determine precision would not be an acceptable practice.

The precision of an instrument can also be improved by averaging the data from multiple sensors operating at the same location. It is conceivable that a number of sensors measuring the same pollutant could be used at the same site and averaged together to increase the precision of the combined measurement.

How to calculate it: There is no one correct method of estimating precision. Precision can be estimated by various statistical techniques using some derivation of the standard deviation. For example, P = Cs / Cm (where P is the precision, Cs is the standard deviation of the measurements, and Cm is the measurement mean at a given concentration).

Learn more:
www.epa.gov/ttn/amtic/files/ambient/monitorstrat/precursor/07workshopmeaning.pdf

Figure C-2 is a time series showing measurements of 1-minute (red) and 15-minute (green) averaged ozone measurements. The line showing the 15-minute measurements is significantly more representative of the sensor's true response.

[39] www.epa.gov/quality/qs-docs/g5-final.pdf.

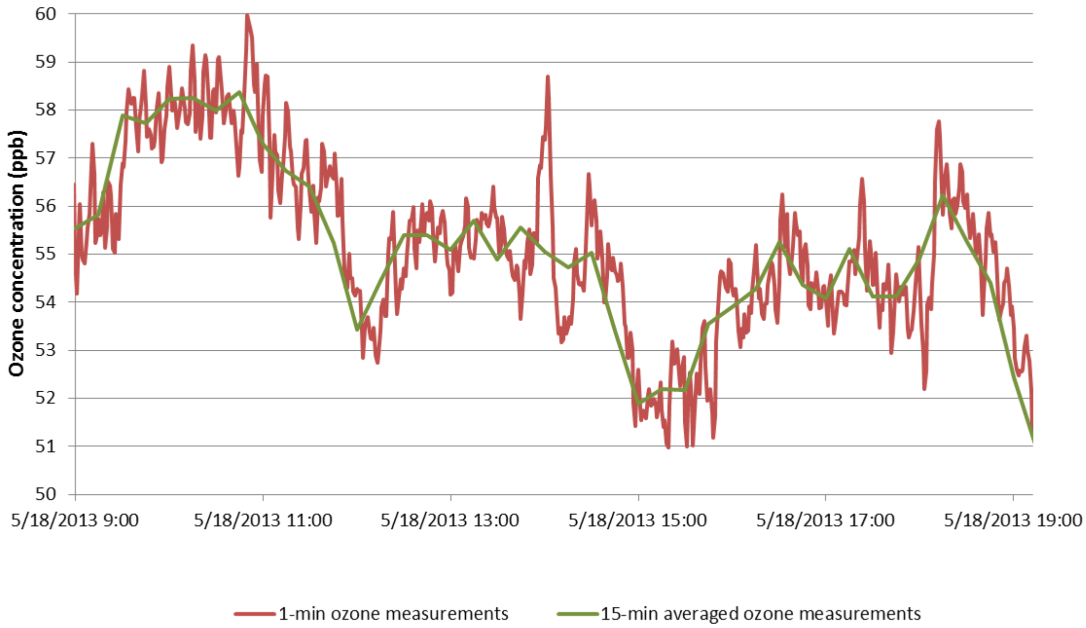

Figure C-2. Time series showing measurements of 1-minute and 15-minute averaged ozone measurements.

Understanding Accuracy, Bias, and Precision

Accuracy is a measure of the overall agreement of a measurement with a known value. Accuracy includes a combination of systematic error (bias) and random error (precision). Reducing systematic and random errors will improve measurement accuracy.

Accuracy is sometimes confused with bias; you may see the terms used interchangeably. EPA recommends using the terms “precision” and “bias,” rather than “accuracy,” to convey the information usually associated with accuracy (see http://www.epa.gov/emap/html/pubs/docs/resdocs/mglossary.html).

Accuracy can be calculated by comparing the mean of a *small* data set to the true value:

$$A = \bar{x} - x_t$$

where $\overline{x}$ is the mean of a small set of data and x_t is the accepted true value. The measurement accuracy of an instrument typically improves with more data, as long as the instrument is unbiased.

In contrast, bias is the consistent, systematic difference between the measurements and the true value. A bias can either be higher or lower than the actual value, and is caused by systematic errors (instrumental, method, or operator errors). A bias cannot be minimized with additional data.

There are several ways to define and explain accuracy, bias, and precision. The National Institute of Standards and Technology (NIST) and the International Union of Pure and Applied Chemistry (IUPAC) provide useful alternatives to those presented here (http://www.itl.nist.gov/ and http://goldbook.iupac.org), and instrumental and chemical analysis text books are also great resources (e.g., Skoog D.A., Holler F.J., and Nieman D, 1998, *Principles of instrumental analysis*, 5th ed., Saunders College Publishing, Philadelphia, PA). The EPA’s guideline is available at epa.gov/ ttnamti1/files/ambient/monitorstrat/precursor/07workshopmeaning.pdf.

Calibration

A calibration procedure checks and adjusts an instrument's measurements by comparing them to a standard, reference, or value[40].

Why it matters: Sensor calibration is vital for producing accurate, usable data. Calibration relates the response of the instrument to the true concentration of a pollutant. Ideally, calibrations are carried out under the same conditions (temperature and humidity ranges, concentration ranges, background air, etc.) as those in which the instrument will collect measurements, because many sensors are strongly influenced by these conditions.

How to perform: Here is the basic approach to calibrating a sensor:

1. **Compare the response of the air sensor with the response of a reference instrument.**
   - There are two main approaches to calibrating an instrument. The first is to do a calibration with standards, in which you introduce some widely accepted reference standard to the sensor. The second is to do a comparison against a reference instrument that has been calibrated with a recognized standard. This can be done by locating the sensor near an air quality station managed by your local authority. This is typically referred to as "collocation." If you decide to collocate, consider doing so for a few days prior to the start, during, and after your measurement period. Locate your sensor as close to the air quality monitor as possible, so that the two devices are measuring the same air quality.
   - Sensor calibrations may also involve using a flow meter to measure air flow through the device if it is a device that pulls air into it.
   - Here are some additional tips regarding calibrations:
     - Calibrations are best done with a reference standard. Such standards are available from many science product vendors.
     - A gas standard is typically delivered from a compressed gas cylinder. However, very reactive gases have to be made at the time of calibration because they degrade in a gas cylinder. Ozone is a good example. An ozone generator is needed to produce known ozone concentrations, and these are expensive. It may be better to use the collocation calibration option for this pollutant. NO_2 can be delivered from a gas cylinder, but it degrades fairly quickly. Small bottles of NO_2 test gas have one-year expiration dates.
     - Examples of particle standards are Urban Particulate Matter (UPM), Arizona Road Dust (AZRD), and Polystyrene Latex Spheres. The UPM and AZRD are sold as powders that would be blown ("resuspended") into a large volume (i.e., a tank or bag) using a clean compressed-air source and then introduced to the

[40] http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20001QWV.txt.

instrument. A reference measurement will be needed to determine the mass concentration of the resuspended standard. Polystyrene latex spheres (PSLs) are solids emulsified in water that are aerosolized using a nebulizer or atomizer (a sprayer) and then dried using dilution air or a diffusion drier. PSLs have a very narrow size range and are used for calibration sensor sizing performance. Even so, developing and delivering such particles requires very sophisticated laboratory equipment and therefore one unlikely available for citizen scientists to perform themselves.

- Sometimes standards have to be mixed with a clean air source. Medicinal grade breathing air or industrial grade nitrogen may be enough for your purposes, but there are other, more expensive, options. You can buy cylinders of high purity (HP) and ultra-high-purity (UHP) gases, as well as “Zero Air,” from specialty gas suppliers. You can also buy Zero Air generators.
- Calibrations done under very controlled environments, where contaminants and environmental conditions (temperature and relative humidity) are known and held constant, may not be directly relevant to real-world applications. It is important that any laboratory calibrations be complemented with field calibrations. For example, ozone sensors calibrated in ambient air were shown not to suffer from the temperature and relative humidity effects that were observed in these same sensors during a laboratory-based calibration[41].

2. **Create a calibration curve that relates the responses of the air sensor to the reference instrument.**
   - The idea behind a calibration is to convert a raw instrument response, which is usually some sort of electronic signal, into useful units (e.g., concentration). This is done by creating a scatter plot comparing measurements made by your sensor device to the standard concentrations or measurements of the reference instrument, and then relating them using a mathematical equation.
   - The amount of data needed to develop a good calibration curve (i.e., the sensor response compared to the target concentration) depends on the linearity of sensor response (see Sensor Response discussion below) to the target pollutants. For example, an initial standard calibration for an ozone sensor may consist of a calibration point collected with no ozone being available, followed by between 4 and 6 calibration events across the range of concentrations that you expect to see during the measurement period.

3. **Repeat the calibration periodically and track the changes in the calibration curve with time.**
   - Subsequent calibrations should be done periodically (e.g., daily, weekly, quarterly, semi-annually, annually) The timing and need for these events will be highly dependent upon the sensor being used and the purpose for how it is being used. It is

[41] Michel Gerboles and Daniela Buzica (2009) Evaluation of micro-sensors to monitor ozone in ambient air. Joint Research Centre, Institute for Environment and Sustainability, Transport and Air Quality Unit, Via E. Fermi, I – 21027 Ispra (VA) http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/10477/1/eur23676.pdf.

important that sensors are calibrated regularly to address changes in performance over time. Pre-calibrated sensors are available from some manufacturers.

- Instruments that drift or change in performance quickly need more frequent calibrations than very stable instruments.
- Track your calibrations to see how the sensor response is changing. You will pick up on problems more quickly by doing this.

Learn more:

- http://www.epa.gov/fem/pdfs/calibration-guide-ref-final-oct2010.pdf
- NIST Standard Reference Materials can be found at http://www.nist.gov/srm/

Detection Limit

The lowest concentration that can be determined as being above zero by a single measurement at a stated level of certainty is the detection limit[42]. There are many types of detection limits. One often used is referred to as the Method Detection Limit (MDL)[43], and it is typically defined as 99% confidence that the measurement is not instrument noise (Figure C-3).

Why it matters: Environmental pollutants can often be present in very low concentrations, particularly when measurements are being made far from the source of the pollution. To be useful, sensors must be able to measure pollutants over the ranges of concentrations typically seen in the atmosphere. One instrument with a higher MDL may be appropriate near a source location, but an instrument with a much lower MDL (more able to measure lower concentrations) may be needed far away from sources, in locations where pollutant concentrations have become diluted. Typical pollutant ranges are shown in Table 2-2, although depending on the situation, an instrument may or may not need to measure well at the lower end of the concentration range.

The detection limit is usually provided by the manufacturer. You may want to ask how the manufacturer determined the detection limit. A sensor's detection limit may vary over time, so if you routinely measure very low concentrations, consider measuring the detection limit frequently. This can be done by diluting the calibration gas until the instrument cannot reliably detect the pollutant of interest anymore. If such equipment is not available, comparing your data to those of a reference instrument measuring low, regional background concentrations can be useful.

Learn more:

- http://www.epa.gov/fem/calibration.htm
- http://www.epa.gov/fem/pdfs/Env_Measurement_Glossary_Final_Jan_2010.pdf

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[42] http://www.epa.gov/quality/qs-docs/g5-final.pdf.

[43] See 40 CFR Part 50 Appendices L and N, 40 CFR Part 58 Appendix A. Also refer to Appendix D of the *EPA Quality Assurance Handbook for Air Pollution Measurement Systems Volume II,* www.epa.gov/ttnamti1/files/ambient/pm25/qa/QA-Handbook-Vol-II.pdf.

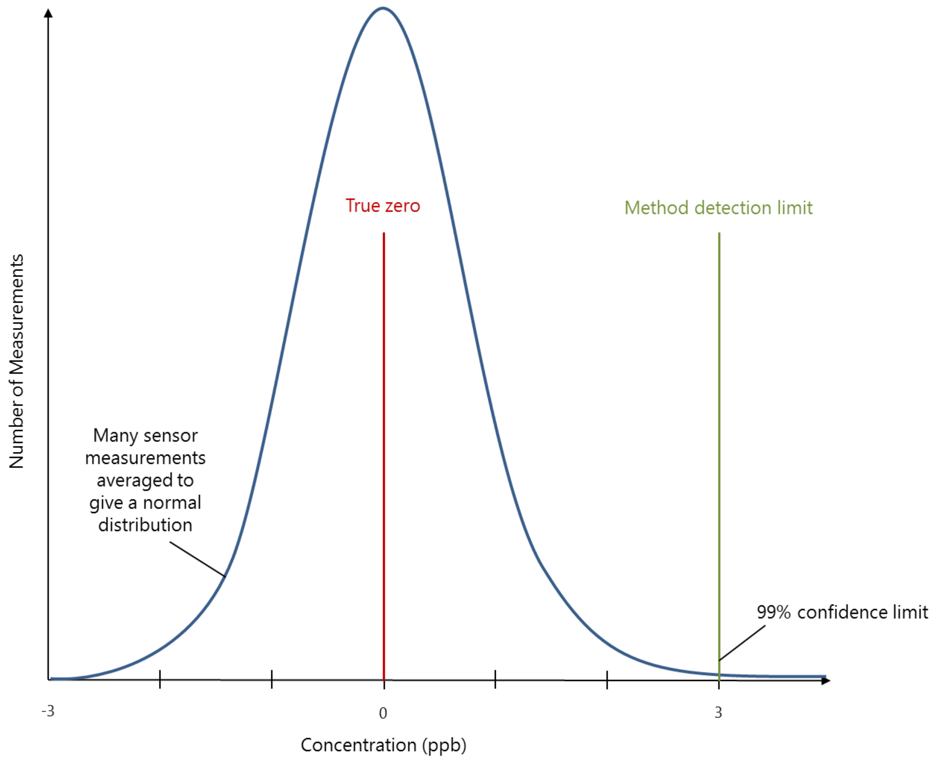


Figure C-3. Graphical representation of a detection limit. (source: EPA's Air Toxics Workbook)[44].

Response Time

Response time is the amount of time required for a sensor to respond to a change in concentration.

Why it matters: A sensor that responds quickly may be useful for mobile monitoring and for observing very rapid changes in pollutant concentrations. A sensor that responds slowly may be more suited to stationary monitoring of pollutants that vary in concentration gradually. The measurement duration and frequency are governed by the sensor response time.

Learn more: Most manufacturers characterize sensor response times as a means to compare the specifications between sensors. They typically use t_{90} for fast-responding sensors and t_{50} for sensors with slower responders. The t_{90} is the time taken by the sensor response to get to 90% of the pollutant or standard concentration that is being measured. It is measured by first delivering zero air to the sensor and then suddenly switching on a flow of the pollutant or standard of interest. Similarly, the t_{50} is the time taken by the sensor response to get to 50% of the pollutant or standard concentration that is being measured. These concepts are illustrated in Figure C-4.

[44] Hafner H.R., Charrier J.G., and McCarthy M.C. (2009) Air toxics data analysis workbook. Prepared for the U.S. Environmental Protection Agency, Research Triangle Park, NC, by Sonoma Technology, Inc., Petaluma, CA, STI-908304-3651-WB, June. Available at http://www.epa.gov/ttnamti1/files/ambient/airtox/workbook/AirToxicsWorkbook6-09.pdf.

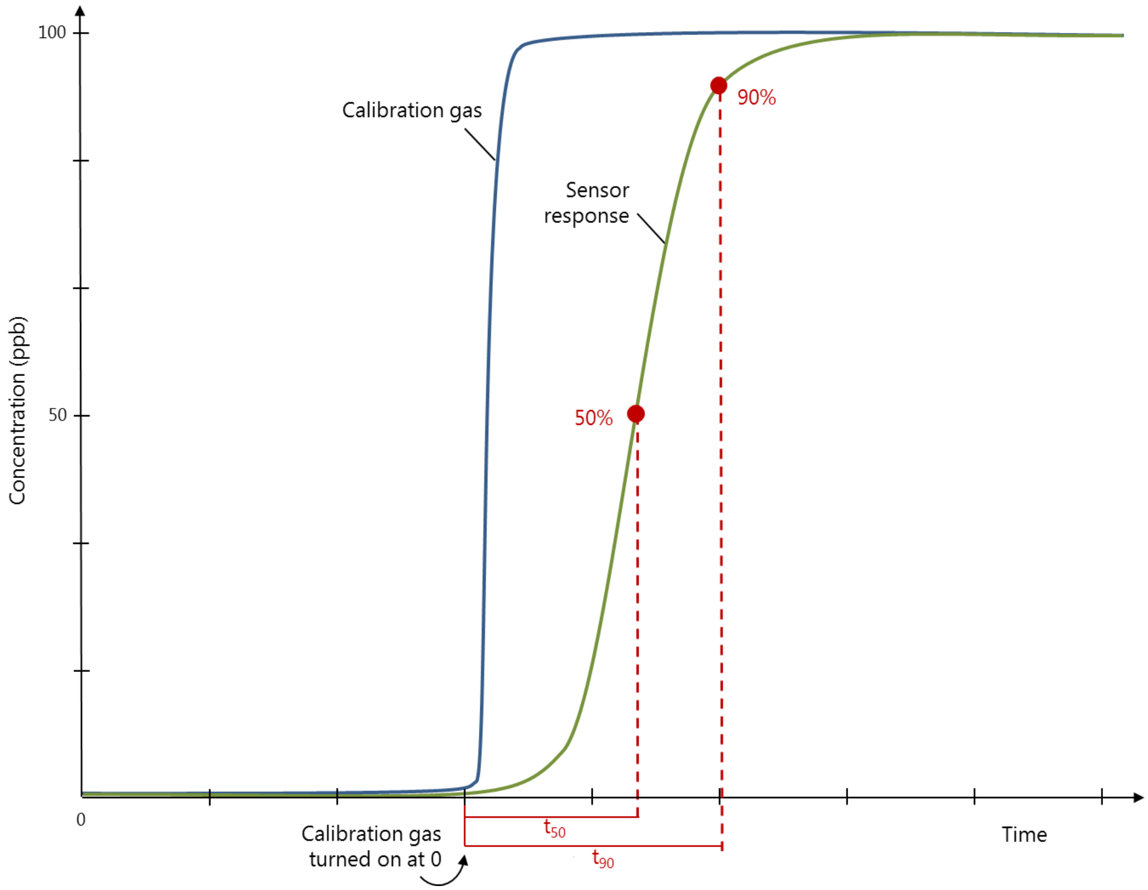
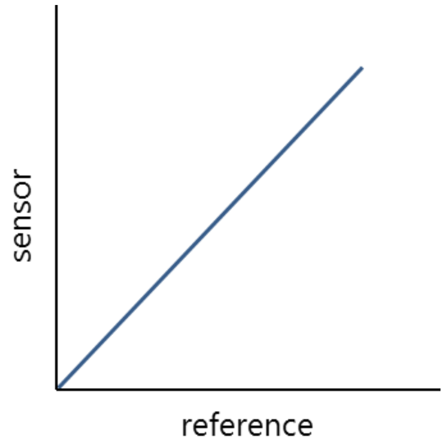


Figure C-4. Response time (t_{50} and t_{90}) of an instrument to a calibration gas.

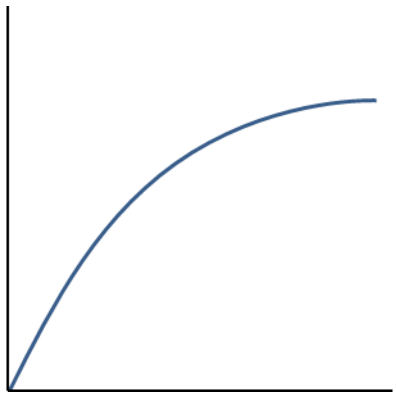
Sensor Response

A useful sensor response is composed of a unique response for each concentration measured. Such a response is called a monotonic increase.

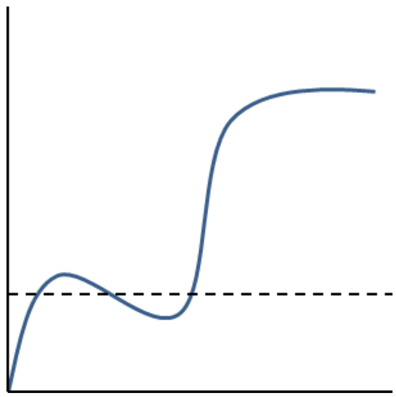
Why it matters: Sensor responses to pollutant concentrations are normally related using a mathematical equation, and they are typically single valued (i.e., unique to each pollutant concentration) in the region of interest. The sensor response does not need to be linear, but it needs to be quantifiable through an equation; polynomial, power law, or exponential equations are all acceptable. Figure C-5 shows examples of sensor response functions.



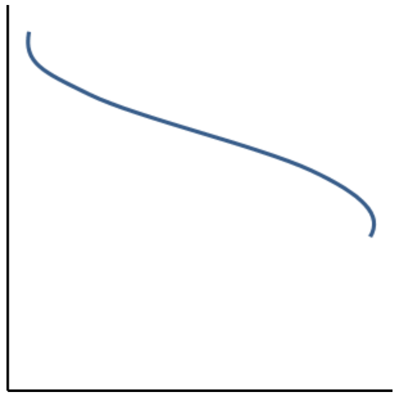
Ideal



Curved, but the sensor output becomes constant even though reference concentrations are still increasing



To be most useful, a calibration curve must only increase, or only decrease, and not do both. This calibration curve both increases and decreases, causing the calibration curve to <u>be difficult to use properly</u>. The dashed line shows that one sensor value can be interpreted as three concentrations.



Only the linear (straight) region in the middle of the calibration curve is useful in this example because curves at the end start to curve inappropriately.

Figure C-5. Examples of sensor responses as a function of concentration.

Measurement Duration

Measurement duration is the length of time over which a measurement is collected (e.g., 1 minute, an hour).

Why it matters: Shorter measurement times allow you to see more rapidly changing concentrations. The minimum measurement duration depends on the sensor response time and other factors. There are situations in which you might want to average measurements over longer time durations to:

- Improve the precision of measurements from less precise sensors, or
- Reduce the size of a data set to make it more manageable during processing. For example, you might average 1-second data to 1-minute or 5-minute data if these measurement durations will still give enough detail to meet your study objectives. It is important to ensure that the measurement duration of your sensor is compatible with your application. In order to capture variations in concentration by location, a sensor on a mobile platform (e.g., walking) may require a shorter measurement duration than a stationary sensor would require. It is very difficult to accurately collect data from fast-moving vehicles; this is not really practical with current sensor technology.

Measurement Frequency

Measurement frequency describes the number of measurements collected per unit of time.

Why it matters: The measurement frequency will be dictated by your study objectives and will affect the sample collection and precision aspects of your data quality objectives[45].

- *Sample Collection*: measurement frequency refers both to how often you make measurements (i.e., one hour per week) and how often measurements are made during this time (i.e., one measurement per minute). This will affect how much data coverage

[45] Data quality objectives describe when, where, how often, and to what precision you need samples to be taken to answer the scientific question you are interested in.

you have to describe the problem or process you are looking at. If you intend to evaluate a long-term trend in concentrations at a particular location, you may choose to collect measurements every five minutes for an hour, on a different day each week for a year. On the other hand, if you would like to evaluate how concentrations change over the course of a day next to a source location, you may want to collect measurements once every minute for 24 hours over several consecutive days.

- *Precision*: the more frequently data are collected over a given time period, the more the data's precision increases, because there are more data to cancel out random errors in the measurements. However, there is a point at which collecting data more frequently produces diminishing returns on improving precision and instead gives you too much data to manage. Imagine collecting 60 data points each hour for 24 hours for one week. That means reviewing and analyzing more than 10,000 pollutant concentration measurements!

Data Grouping

Data grouping involves averaging data over time and/or space.

Why it matters: Data are often grouped to facilitate comparison to measurements from another instrument, health-based benchmarks, or environmental standards. For example, the NAAQS listed in Table 2-2 represent limits on concentrations that have been grouped over a range from 1 hour to 1 year. The NAAQS for ozone is 0.075 ppm averaged over eight hours.

Data grouping helps improve the quality, usefulness, and manageability of your data. The exact type of grouping will depend on your application and the question you are trying to answer. For example, if you are interested in observing a pollutant concentration trend over the course of a month, you may want to group your data in 1-hour or 24-hour averages. You will be able to see how the concentrations change, but averaging will reduce the amount of data you are working with to a manageable size. On the other hand, if you would like to understand how a plume of gas coming from an industrial facility moves over your community, you may prefer to use a shorter averaging period, such as 1-minute, to capture it's movement.

Selectivity

The ability of a sensor to respond to a particular pollutant, and not to other pollutants, is called selectivity.

Why it matters: Sensors are most useful when they only respond to a single pollutant or several pollutants of interest. However, air is composed of a wide variety of chemical compounds, and some sensors may respond simultaneously to pollutants of interest as well as other substances in the air. For example, some air quality sensors that measure ozone also respond to changes in nitrogen oxides and sulfur dioxide concentrations, providing a deceptively high signal. On high quality instrumentation, the manufacturers have developed techniques for eliminating or reducing such concerns.

Interferences

Interferences are factors that hinder, obstruct, or impede the ability of a sensor to make accurate measurements.

Why it matters: As mentioned under the Selectivity consideration, an ideal sensor would only respond to the pollutant or pollutants of interest. However, sensors may respond significantly to other pollutants in a way that is indistinguishable from the response to the target pollutant. Specifically, sensor readings may be affected by:

- pollutants or other chemical compounds that are not of interest
- weather conditions (e.g., fluctuations in wind speed, humidity, and temperature)
- radio frequencies
- power fluctuations
- vibration
- dirt, dust, and insects

Interferences may have a positive or negative effect on a sensor signal. Also, it is possible for a sensor to respond to several different interferences simultaneously. Manufacturers usually disclose pollutants and meteorological parameters that may impact sensor performance but not the response factor, which would be useful to determine the importance of the interference. Before using a sensor to monitor air quality, consider possible sensor interferences, test for them, and minimize them if possible.

Sensor Decay and Expiration

Sensor decay and expiration refer to a permanent decline in sensor performance due to any number of factors. In general it means the sensor loses its ability to take meaningful measurements.

Why it matters: Some chemical compounds in the atmosphere can react with and damage sensors in a non-reversible way, limiting the ability of the sensor to respond as well to the pollutant of interest as it did initially. Note that some sensors have an expiration date, even if they are never used and are in their original packaging.

Dynamic Range

An instrument's dynamic range is the concentration range from minimum to maximum values that the instrument is capable of measuring[46].

Why it matters: Concentration ranges vary by pollutant and by proximity of the sensor to the source. In some cases, concentrations may be either too low or too high for a sensor to detect. It is important to consider the range of concentrations you expect to monitor and whether your sensor will be able to collect measurements throughout this range. Typical ambient concentration ranges for each pollutant discussed in this document are provided in Table 2-2.

[46] http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20001QWV.txt

Drift

A gradual change in instrument response to a constant, quantitative characteristic (i.e., a standard concentration or zero air) is called drift.

Why it matters: Instrument drift may lead a user to inaccurately conclude that concentrations have increased or decreased over time. Drift can be positive or negative, and it may occur due to a variety of reasons. For example, the sensor may respond to changes in weather conditions, to sensor poisoning, or, in the case of optical sensors, to light sources becoming less powerful or less efficient over time. Figure C-6 shows an example of an NO_2 measurement that drifted. One way to overcome drift is to calibrate the sensor frequently so that the instrument only drifts a small amount between each recalibration. The frequency of calibration needed will depend on how much drift occurs.

Figure C-6. graphically illustrates drift using a time series of measurements from a sensor (blue line) experiencing significant drift compared with the true concentration of NO_2 (green line).

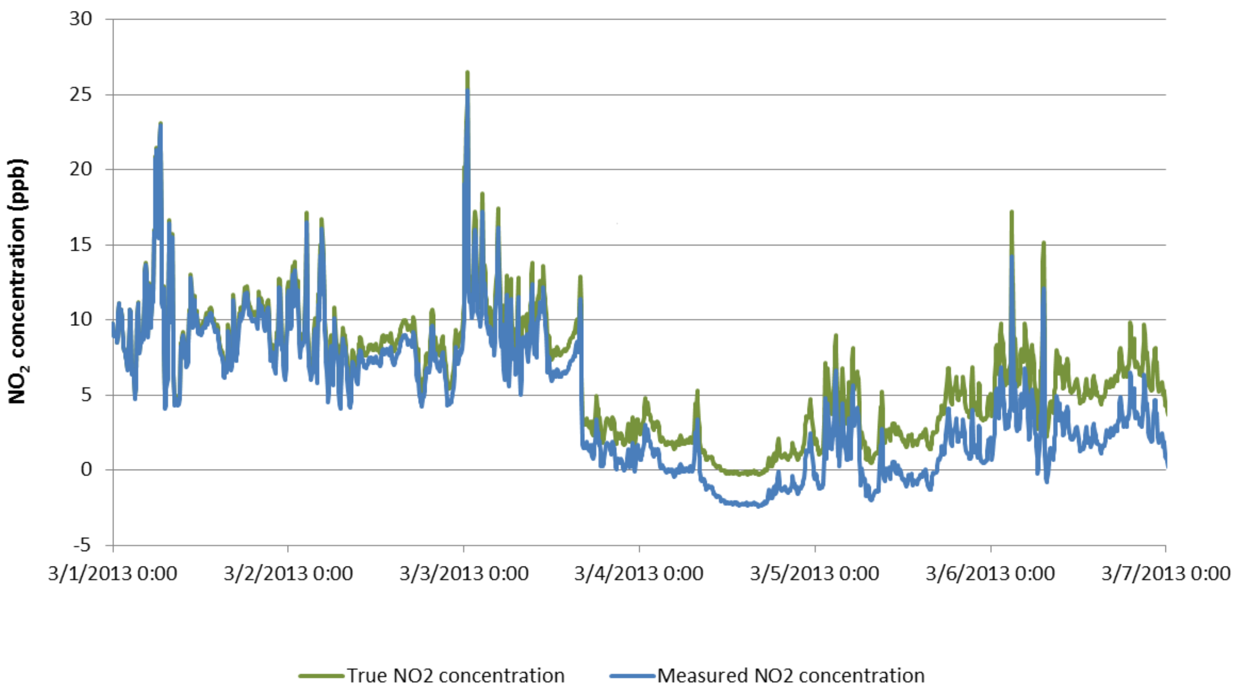


Figure C-6. Illustration of Drift.

Accuracy of Timekeeping

Timestamp accuracy describes the correctness and reliability of the time value recorded as each measurement is collected.

Why it matters: Time keeping accuracy is most important when you need to compare measurements made by different instruments. This type of accuracy becomes more critical for comparing data showing large, rapid changes in concentration or data from instruments with high measurement frequencies.

Climate Susceptibility

Climate susceptibility is a measure of an instrument's ability to endure variation in meteorological conditions, including changes in temperature, humidity, and sun exposure.

Why it matters: Air quality instruments are expected to operate in a wide range of atmospheric conditions. A sensor is most useful if it can operate robustly in many different environments, but it needs to operate well in the intended use environment at the very least. It is important to consider which sensor is best suited for the climate of your study location. For example, relative humidity and temperature influence the performance of electrochemical sensors. Consider whether the instrument enclosure would benefit from being air-conditioned, or whether environmental effects on the measurements can be corrected after data collection.

Learn more: Michel Gerboles and Daniela Buzica (2009) found that ozone sensors calibrated in a laboratory reactor suffered from temperature and relative humidity effects, although these problems were removed when calibrations were done at the field sites using ambient air. See *Evaluation of Micro-Sensors to Monitor Ozone in Ambient Air, 2009.* Michel Gerboles and Daniela Buzica, *Joint Research Centre, Institute for Environment and Sustainability, Transport and Air Quality Unit, Via E. Fermi, I – 21027 Ispra (VA)* http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/10477/1/eur23676.pdf.

Data Completeness

The amount of valid data obtained from a measurement system, compared to the amount that was expected to be obtained under correct, normal conditions, is called data completeness[47].

Why it matters: Data completeness is a key to producing high-quality, representative data. Missing data can significantly hinder analyses, minimizing the strength of conclusions drawn. EPA's guidance for regulatory data includes a requirement to achieve 75% data completeness over the required period of time (hourly, daily, quarterly, annually). Commonly, reductions in data completeness are due to data transmission problems; data storage errors; power loss and the time required for subsequent restart (see Response to Loss of Power discussion below); the need for frequent or long-duration calibrations; and time the instrument is offline for repair. For data transmission, if data will be transferred using a wireless connection, the reliability of the connection is very important. Onsite data storage may also be considered so that data are not lost if the wireless connection is interrupted.

Learn more: http://www.epa.gov/ttn/oarpg/t1/memoranda/pmfinal.pdf; 40 CFR 50 contains Appendix A-N (NAAQS data completeness)

[47] http://www.epa.gov/ttn/amtic/files/ambient/monitorstrat/precursor/07workshopmeaning.pdf.

Response to Loss of Power

This refers to the amount of time that an instrument requires after shutdown to warm up and resume measurement, as well as the consistency of the sensor response prior to and after shutdown.

Why it matters: If a sensor requires a large amount of time to warm up and resume measurement after a loss of power, data continuity and completeness can be significantly affected. Once the sensor resumes collecting measurements, its response should ideally be the same as before the loss of power.

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