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The Enhanced Air Sensor Guidebook

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Center for Environmental Measurement and Modeling

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The Enhanced Air Sensor Guidebook

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Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

AAPCA	Association of Air Pollution Control Agencies
AMTIC	Ambient Monitoring Technology Information Center
API	Application Programming Interface
AQI	Air Quality Index
AQMD	Air Quality Management District
AQ-SPEC	Air Quality Sensor Performance Evaluation Center
AQS	Air Quality System
ATSDR	Agency for Toxic Substances and Disease Registry
b	intercept
BC	black carbon
BTEX	benzene, toluene, ethylbenzene, and xylene
CAA	Clean Air Act
CARB	California Air Resources Board
CEMM	Center for Environmental Measurement and Modeling
CEN	European Committee for Standardization
CFR	Code of Federal Regulations
CH_4	methane
cm^3	cubic centimeter
CO	carbon monoxide
CO_2	carbon dioxide
CSN	Chemical Speciation Network
CV	coefficient of variation
°C	degrees Celsius
DIY	Do-it-Yourself
DMS	Data Management System
EC	electrochemical
EU	European Union
FAQs	Frequently Asked Questions
FEM	Federal Equivalent Method
FRM	Federal Reference Method
GPS	global positioning system
GMI	Global Methane Initiative
H_2S	hydrogen sulfide
HAPs	hazardous air pollutants
HEI	Health Effects Institute
Hg	mercury
ID	identification
IMPROVE	Interagency Monitoring of Protected Visual Environments
IQ	intelligence quotient
ISA	Integrated Science Assessment
IRIS	Integrated Risk Information System
IT	information technology
JRC	Joint Research Centre
LoRa	Low-power Wide Area Network
m	slope
MAE	mean absolute error
MBE	mean bias error
MEE	China Ministry of Ecology and Environment
MeHg	methylmercury
MOS	metal oxide sensors

N	number of data points
NAAQS	National Ambient Air Quality Standards
NACAA	National Association of Clean Air Agencies
NATTS	National Air Toxics Trends Stations
NCore	National Core Multipollutant Monitoring Network
NH_3	ammonia
NIOSH	National Institute for Occupational Safety and Health
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
NSIM	non-regulatory supplemental and informational monitoring
NSRDB	National Solar Radiation Database
NTAA	National Tribal Air Association
OAQPS	Office of Air Quality Planning and Standards
ORD	Office of Research and Development
O_3	ozone
PAHs	polycyclic aromatic hydrocarbons
Pb	lead
PID	photoionization detector
PM	particulate matter
$PM_{1.0}$	particles with diameters generally less than 1.0 micrometers
$PM_{2.5}$	particles with diameters generally less than 2.5 micrometers; also called fine particulate matter or fine PM
PM_{10}	particles with diameters generally less than 10 micrometers
ppb	parts per billion
ppm	parts per million
QA	quality assurance
QAPP	Quality Assurance Project Plan
QC	quality control
R^2	coefficient of determination
RETIGO	REal TIme GeOspatial Data Viewer
RH	relative humidity
RMSE	root mean square error
SD	standard deviation
SIP	State Implementation Plan
SLAMS	State and Local Air Monitoring Station
SO_2	sulfur dioxide
SO_x	sulfur oxides or oxides of sulfur
SOP	standard operating procedure
T	temperature
tVOC	total volatile organic compounds
UFP	ultrafine particles; particles with diameters generally less than 0.1 micrometers
UL	Underwriters Laboratories
UV	ultraviolet
$\mu g/m^3$	micrograms per cubic meter
µm	micrometers
U.S.	United States
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VOCs	volatile organic compounds
WHO	World Health Organization

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Executive Summary

In 2014, the United States Environmental Protection Agency (U.S. EPA) published the original *Air Sensor Guidebook* to help those interested in using sensors to collect air quality measurements and interpret sensor data. The Air Sensor Guidebook has been one of the most popular resources on the U.S. EPA's Air Sensor Toolbox website. The guidebook was intended to provide basic foundational knowledge on topics including:

- Background information on common air pollutants and air quality
- Selecting appropriate sensors for different applications
- Data quality considerations, and
- Sensor performance for different applications

The initial target audience for the *Air Sensor Guidebook* was limited to participatory scientists and sensor manufacturers/developers. Since 2014, the sensor user community has grown to include individuals, communities, schools, researchers, environmental agencies (e.g., air quality, environmental quality, natural resources, health), industry, medical professionals, emergency responders, technology developers, data integrators, and more.

Recognizing the ever-increasing availability of sensors, expanding scientific knowledge, and availability of best practices to support sensor use, the U.S. EPA significantly updated the 2014 Guidebook. The refreshed version, *The Enhanced Air Sensor Guidebook*, includes updated content and new topics that incorporate best practices, current knowledge, and recommendations on sensors.

The goal of the enhanced Guidebook is to support users in planning and collecting air quality measurements using air sensors. This Guidebook can help sensor users:

- Learn the basics of air quality, air pollution monitoring, and air sensors
- Plan and conduct an air quality monitoring study
- Select, setup, and use air sensors
- Analyze, interpret, communicate, and act on results
- Understand the basics of air sensor performance

The enhanced Guidebook also contains expanded resources and content in the Appendices including: 1) *General resources* (e.g., air quality information, air sensor performance, data analysis tools), 2) a list of *'Questions to Consider when Planning, Collecting, and Sharing Your Data'* to prepare sensor users for questions to expect from others, 3) *Checklists* for quickly determining how to select sensors, items to look for in a user manual, and maintaining air sensors, 4) information on *data handling* and the *Air Quality Index*, 5) education on *Interpreting Sensor Performance Evaluation Results*, and 6) a *glossary* of terms used in the guidebook.

While this guidebook may not exhaustively answer every question air sensor users may have, it is provided as a resource to help support the user community in effectively using this class of technology to support their air quality monitoring needs.

Chapter 1

Introduction to Air Sensors and the Guidebook

This new and expanded Air Sensor Guidebook empowers communities, environmental agency officials, researchers, students, educators, and others to plan for, select, and operate air sensors to meet specific needs.

This chapter provides:

- Background information about air sensors,
- Our purpose in providing this Enhanced Air Sensor Guidebook,
- Key differences between the 2014 Guidebook and this enhanced version, and
- The intended audience of the guidebook.

1.1 Background on Air Sensors

Air sensors are a class of non-regulatory technology that are lower in cost, portable, and generally easier to operate than monitors used for regulatory monitoring purposes. Air sensors and regulatory monitors differ in that regulatory monitors are the gold standard and are designed to meet strict performance requirements for use in regulatory monitoring. These differences are discussed in more detail in Chapter 2.

Air sensors typically provide relatively quick or instant air pollutant concentration measurements and allow for measurement of air quality in more locations. The term air sensor often describes an integrated set of hardware and software that uses one or more sensing elements (sometimes called sensors or other terms) to detect or measure pollutant concentrations. Figure 1-1 shows the typical air sensor components, which vary from one manufacturer to another. Most air sensors include a power source, components to detect air pollutants and weather parameters, electronics to transmit data (e.g., cellular), and a microprocessor to control the devices. Some air sensors may include a battery, display screen, and a global positioning system (GPS) component to determine location. Sensors that transmit data may connect to cloud servers that store, process, and provide access to data. Additionally, data may be displayed on maps or graphical plots.

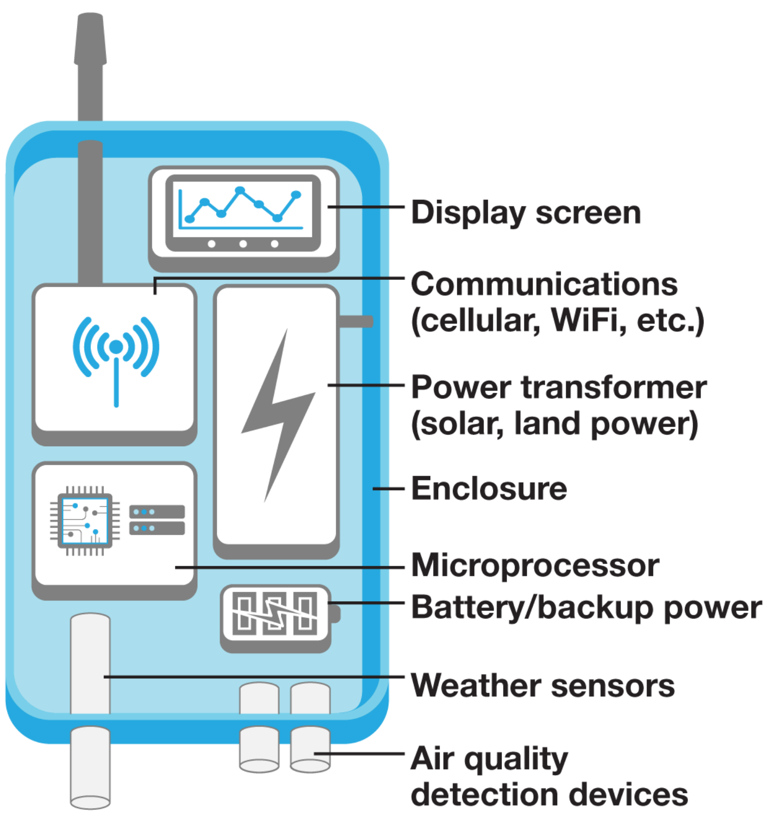


Figure 1-1. Typical Air Sensor Components

Advancements in microprocessors and miniaturization have led to a rapid expansion in the availability of air sensors to measure a variety of air pollutants. As air sensors have become more accessible worldwide, there has been a dramatic increase in their use for measuring air quality conditions and there is greater access to publicly available sensor data sets.

The United States Environmental Protection Agency (U.S. EPA) has identified that a primary use of air sensors is for non-regulatory supplemental and informational monitoring (NSIM) applications. Table 1-1 summarizes examples of these applications. Other potential applications for air sensors include mobile monitoring, personal exposure monitoring, indoor air monitoring, among others. Figure 1-2 shows examples of how air sensors may be used for NSIM and other applications.

Table 1-1. Overview of Non-Regulatory Supplemental and Informational Monitoring Applications (NSIM) for Air Sensors

Category	Description	Common Examples
Spatiotemporal Variability	Characterizing a pollutant concentration over a geographic area and/or time. *Is pollution higher in the morning at a location?*	• Daily trends • Gradient studies • Air quality forecasting • Participatory science* • Education
Comparison	Analyzing differences and/or similarities in air pollution characteristics against a threshold value or between different networks, locations, regions, time periods, etc. *Does a location show high pollution levels, but other locations do not?*	• Hotspot detection • Data fusion • Emergency response • Supplemental monitoring
Long-term Trend	Characterizing changes in pollutant concentrations over a long time. *How did pollution concentrations change at a location over a 5-year period?*	• Long-term changes • Epidemiological studies • Model verification

*Participatory science is also referred to as citizen science, community science, volunteer monitoring, or public participation in scientific research (Source: https://www.epa.gov/participatory-science).

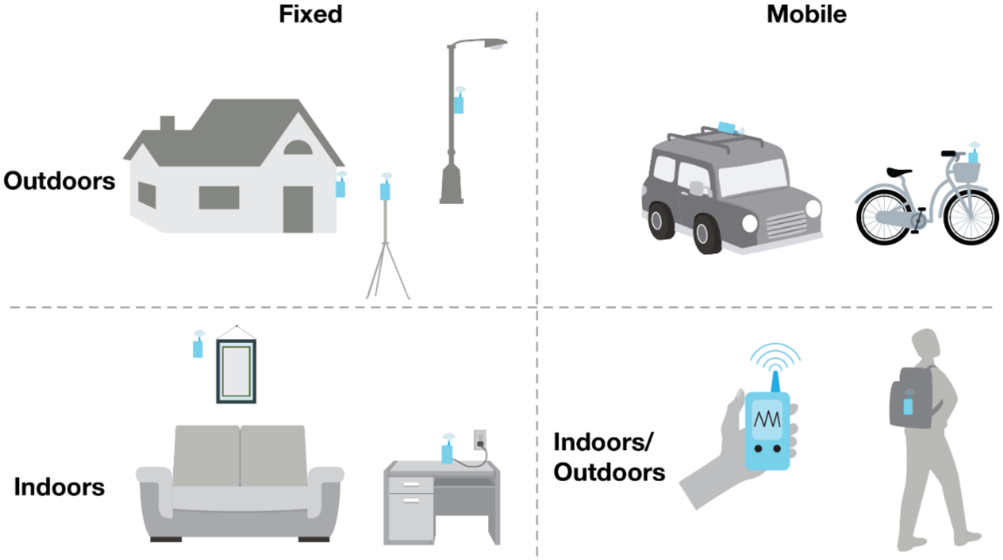


Figure 1-2. Examples of How Users Can Deploy Air Sensors

1.2 Purpose of this Enhanced Guidebook

This Guidebook provides information on air quality monitoring using air sensors. When sited, installed, configured, and operated properly, maintained carefully, and with thoughtful project planning, air sensors can provide useful information for a range of air quality applications. The purpose of this Guidebook is to provide information to those interested in using air sensors, including the basics of air quality, planning and conducting air monitoring, selecting air sensors, considerations for sensor performance, and more.

The Guidebook identifies the best practices for using air sensors and provides recommendations for planning and implementing a study to save time, effort, and money and ultimately help users collect useful data. This Guidebook also offers resources to help you with the many tasks needed to produce, correct, use, and interpret air sensor data, including sensor selection, operating procedures, illustrated figures, checklists, and links to external resources.

1.3 Differences Between the 2014 Guidebook and the Enhanced Version

This ***Enhanced Air Sensor Guidebook*** reflects information gathered from more recent studies, best practices, and scientific literature for rapidly evolving air sensor technologies that have become more available since U.S. EPA released the 2014 Guidebook. This Guidebook includes input from the air quality community, air quality agencies and experts, and U.S. EPA scientists and technical experts.

The U.S. EPA updated Chapter 2 with the latest air quality and health science and expanded air monitoring network and instrument descriptions.

We added new topics or significantly updated existing Guidebook information to incorporate best practices, current knowledge, and recommendations as follows:

- ***Monitoring Using Air Sensors (Chapter 3)***
  - ***Planning and Conducting an Air Quality Monitoring Study*** identifies all tasks involved in monitoring air quality successfully.
  - ***Determining the Purpose for Monitoring*** helps develop an objective for monitoring and matching the air sensor technology to that objective.
- ***Sensor Performance Guidance (Chapter 4)*** provides information about why sensor performance evaluations are necessary and how they are conducted, where results can be found, and how those results can be used to make informed purchasing decisions.

Changes to Appendices include:

- Expanded Appendix A, which lists ***Resources*** including air quality information, sources of real-time and historical data, air sensor performance, data analysis tools, health effect resources, resources for educators, and economic impacts of air pollution.
- Expanded Appendix B, which contains a list of ***Questions to Consider when Planning, Collecting, and Sharing Your Data*** to anticipate questions to expect from others. Answering these questions helps you plan, ensure credibility in your data and results, and allows others to use your data.
- Added the new Appendix C containing checklists for quickly determining 1) ***What to Look for in an Air Sensor***, 2) ***What to Look for in a User Manual***, and 3) ***How to Maintain Air Sensors***.
- Added the new Appendix D to provide information on ***Data Handling and Air Quality Index (AQI) Calculations***.
- Added the new Appendix E which provides education on ***Interpreting Sensor Performance Evaluation Results.***
- Added the new Appendix F which is a ***Glossary*** of definitions for commonly used terms in *this document.*

Lastly, a ***List of Abbreviations*** is provided at the beginning of the document for easy reference.

1.4 Intended Audience

The target audience for the ***2014 Air Sensor Guidebook*** was primarily participatory scientists (i.e., citizen science, community science, volunteer monitoring, and public participation in scientific research) and sensor manufacturers/developers. Since 2014, air sensors are more available, and the number and types of applications continue to expand rapidly. The intended audience for this enhanced Guidebook includes participatory scientists, environmental agency officials, researchers, health professionals, emergency responders, technology developers, educators, and the public.

Resources for More Information

- **U.S. EPA's Air Sensor Toolbox**
  - Information and resources for topics related to air sensors; includes links to other organizations and resources that sensor users may find helpful
  - https://www.epa.gov/air-sensor-toolbox

Chapter 2

Air Quality 101

Air quality is a complex subject as it involves emission of air pollutants, chemical and physical transformation of pollutants, and atmospheric conditions which can move or trap pollutants and affect the speed of chemical reactions. Air quality is measured in a variety of ways. The impacts of air quality on health and the environment vary based on concentration and pollutant type.

This chapter provides:

- Basic knowledge of outdoor air quality,
- Summary of the health and environmental impacts of select air pollutants,
- Overview of the different types of air quality monitoring approaches,
- A review of air quality regulations and indices, and
- Specific information about the Air Quality Index (AQI).

2.1 Overview of Outdoor Air Quality and Air Pollution

Figure 2-1. Poor Versus Good Air Quality

Air quality is a term used to describe how much pollution is present in the air (Figure 2-1). We care about air quality because air pollutants can affect our health and our environment. As indicated by the World Health Organization (WHO), air pollution is a leading cause of death. Several scientific studies (e.g., epidemiologic, exposure) link air pollution to a range of health problems including decreased lung function, aggravation of respiratory and cardiovascular diseases, increased asthma incidence and severity and premature mortality, among many other effects. In addition to causing adverse health effects, air pollutants can also cause adverse environmental effects such as reduced visibility and damage to plant and animal life. Acidic pollutants deposited on the ground, predominantly from rain, harm both land and water ecology and even structures. Furthermore, some pollutants also affect the Earth's energy balance, impacting global climate conditions. See Section 2.2 for further discussion of health and environmental effects.

Air pollution consists of a complex mixture of different chemicals in the form of solid particles (in a range of sizes), liquid droplets, and gases. Air pollution is produced as a result of human-made (i.e., anthropogenic) and naturally occurring pollutant sources. Examples of anthropogenic sources include electricity-generating power plants, cars and trucks, and oil and gas production facilities. Natural pollutant sources include wildfires, dust storms, volcanic activity, and biogenic sources (e.g., plants, soils).

Some of these pollutants are short-lived in the atmosphere (i.e., hours to days), while others are long-lived (i.e., years). Like the weather, air quality changes from day to day, or even hour to hour. 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 (also called deposition). These factors are governed by the type of pollutant and weather conditions, including temperature, sunlight, precipitation, humidity, and wind speed. Strong winds can decrease concentrations by diluting or dispersing pollutants over a larger geographic area, whereas stagnant air (e.g., having no air flow) can lead to pollutant concentrations that gradually increase.

One of the most common causes of stagnant air is a temperature inversion, illustrated in Figure 2-2, which occurs when a layer of cooler air is trapped close to the ground by a layer of warmer air above. Inversions most commonly form overnight when clear skies allow air at the surface to cool faster than the air above. An inversion can last all day, or even for several days. When the air cannot rise, pollution at the surface is trapped and can accumulate, leading to higher concentrations of pollution near the surface.

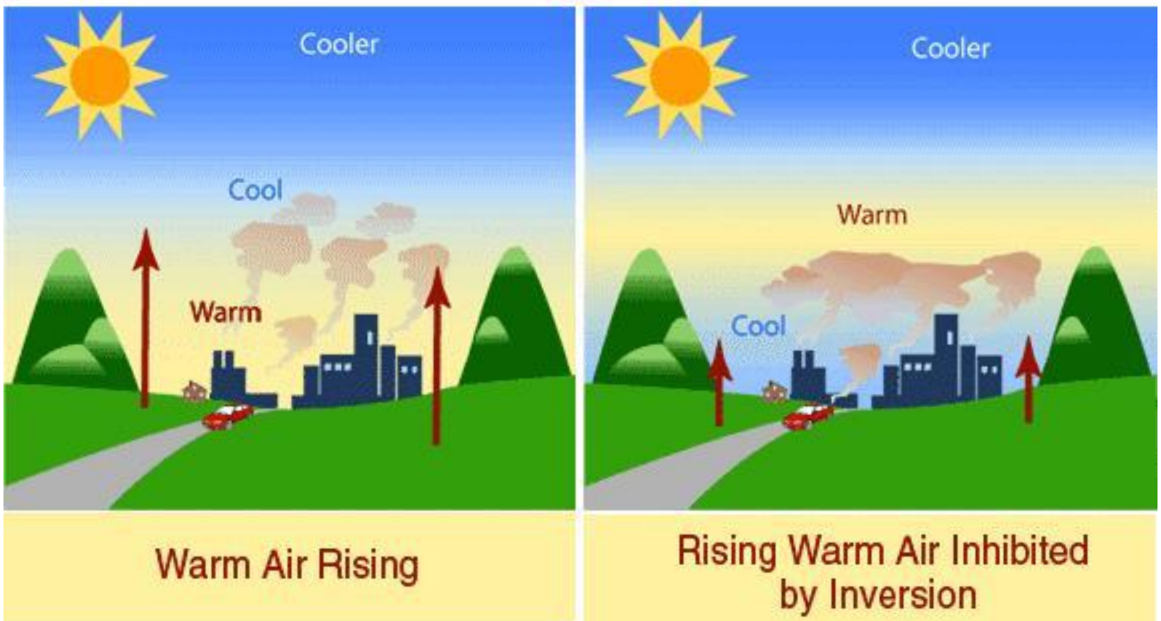


Figure 2-2. Typical Movement of Warm Air in the Atmosphere Versus Warm Air Trapped by a Temperature Inversion

Understanding how weather conditions can influence pollutant concentrations and measurement of pollution is important for gathering accurate information and interpreting trends in data. Figure 2-3 summarizes how conditions in the atmosphere can impact pollutant concentrations.

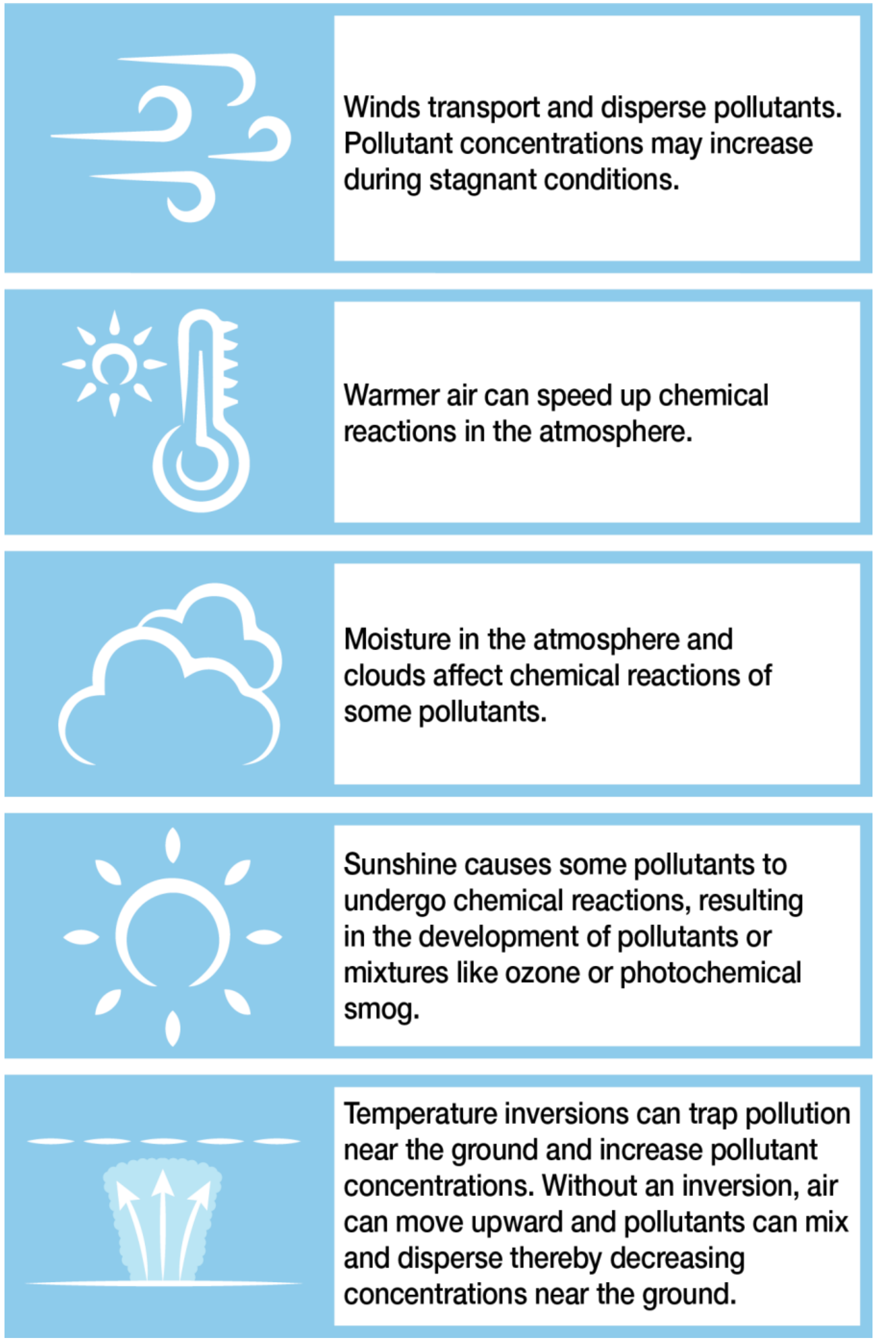


Figure 2-3. Atmospheric Conditions and Their Impacts on Pollutant Concentrations

Air pollutants are generally characterized as either primary or secondary pollutants, as shown in Figure 2-4. **Primary pollutants** are emitted directly from a source. **Secondary pollutants** are formed in the atmosphere by chemical reactions after release from an emission source and, in the outdoor environment, are often found downwind from a source. Pollutant concentrations can vary significantly over space and time because of variations in local emissions, proximity to pollutant sources, chemical reactions, and weather conditions.

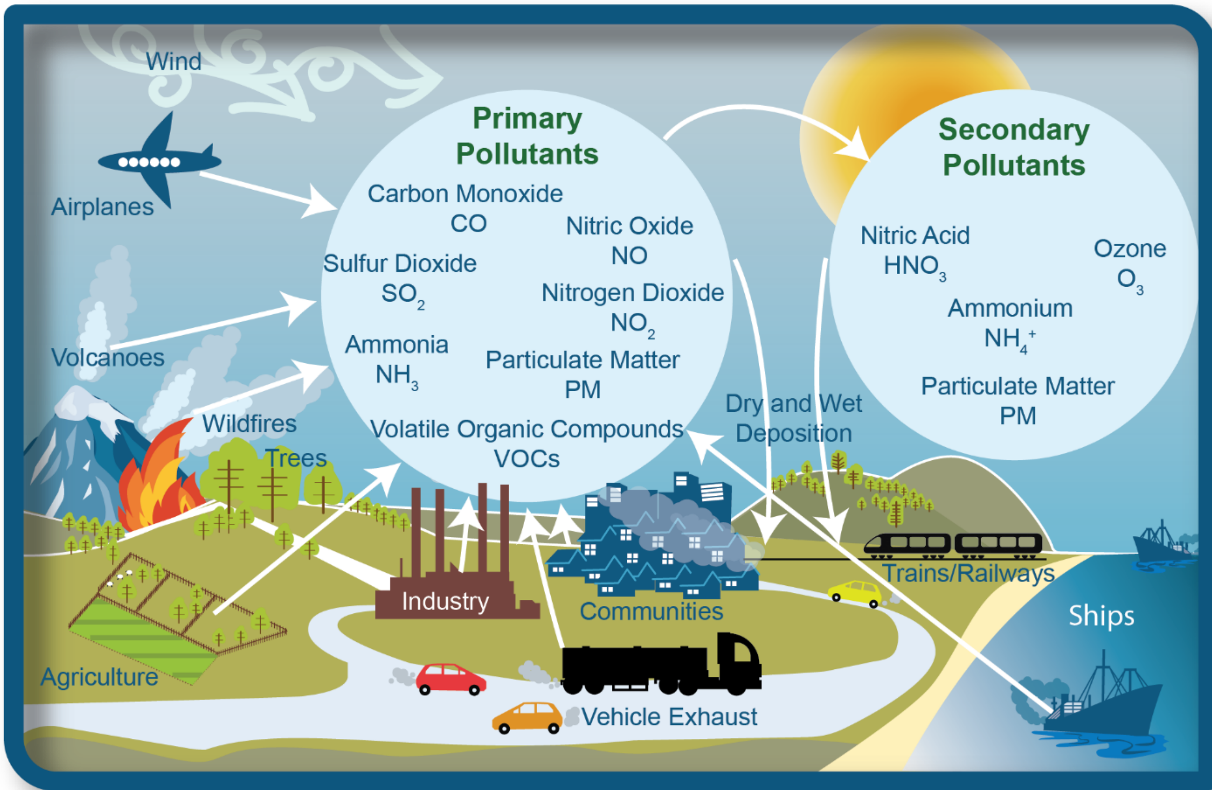


Figure 2-4. Sources of Primary and Secondary Pollutants (Adapted from: https://www.mrgscience.com/ess-topic-63-photochemical-smog.html)

Concentration is the metric for reporting the amount of a pollutant in the air and represents the weight or number of molecules of a pollutant in a volume of air. Common units include micrograms per cubic meter (µg/m^3), parts per million (ppm), and parts per billion (ppb). Less common units include number of particles per cubic centimeter (#particles/cm^3). For example, a concentration of 43 µg/m^3 is the weight of 43 micrograms (a microgram is one millionth of a gram) per cubic meter of air, and parts per billion is the number of units of mass of a pollutant per 1 billion units of the total mass of the air. Units of µg/m^3 are often used for particulate matter (PM) pollution and ppm and ppb are often used for gaseous pollution.

Common pollutants of concern in outdoor air include PM (see Figure 2-5), ground-level ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), lead (Pb), ammonia (NH_3), volatile organic compounds (VOCs), mercury (Hg), airborne particles, and more. Table 2-1 lists these and other common air pollutants, sources, and the range expected in the outdoor air. While PM can range in size, it is typically characterized into one of two groups: PM_{10} and $PM_{2.5}$. PM_{10} particles have diameters that are generally less than 10 micrometers (µm) while $PM_{2.5}$ (also called "fine particulate matter" or "fine PM") have diameters generally less than 2.5 µm (see Figure 2-5).

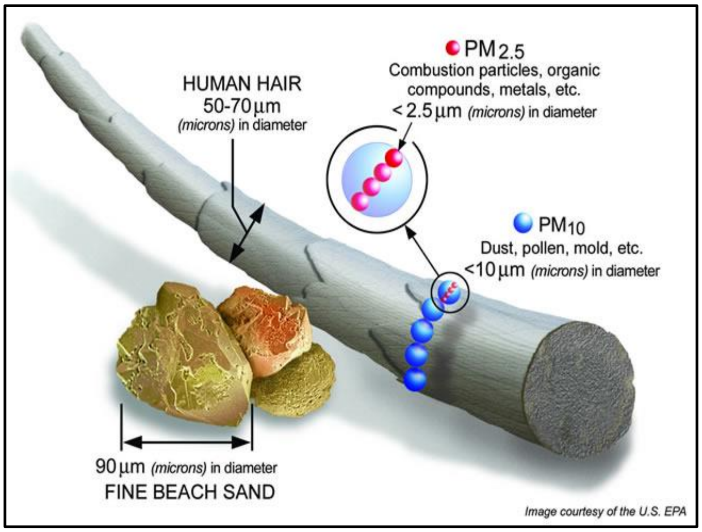


Figure 2-5. Particulate Matter Size Ranges

Table 2-1. Common Air Pollutants, Their Sources, and Concentration Ranges to Expect in Outdoor Air

Pollutant (Abbreviation)	Examples of Outdoor Sources	Typical Hourly Outdoor Concentration Range to Expect within the U.S.
Ammonia (NH_3)	Agriculture, animal husbandry, fertilizers, and mobile sources	0 to 3 µg/m^3
Benzene	Gasoline, evaporative losses from above-ground storage tanks, and mobile sources	0 to 7 µg/m^3 (0.03 to 2.3 ppb)
Black Carbon (BC)	Biomass burning and mobile sources	0 to 15 µg/m^3
Carbon Dioxide (CO_2)	Fuel combustion from electric utilities and mobile sources	350 to 600 ppm
Carbon Monoxide (CO)*	Incomplete fuel combustion from mobile sources and industrial processes	0 to 0.3 ppm
Hydrogen Sulfide (H_2S)	Natural sources (e.g., volcanoes, hot springs, bacterial breakdown of organic matter) and industrial sources (e.g., refineries, natural gas plants, petrochemical plants, food processing, tanneries)	0 to 20 ppm

Pollutant (Abbreviation)	Examples of Outdoor Sources	Typical Hourly Outdoor Concentration Range to Expect within the U.S.
Lead (Pb)*	Smelting, aviation gasoline, waste incinerators, electric utilities, and lead-acid batteries	0 to 0.1 μg/m^3
Mercury (Hg)	Combustion of coal, oil, and wood	0.001 to 0.17 μg/m^3
Methane (CH_4)	Industry (e.g., natural gas operations), agriculture, and waste management	1,500 to 2,000 ppb
Nitrogen Dioxide (NO_2)*	Fuel combustion from mobile sources and electric utilities	0 to 50 ppb
Ozone (O_3)*	Formed via ultraviolet (UV) radiation in sunlight and the presence of other key pollutants (e.g., nitrogen oxides, volatile organic compounds)	0 to 125 ppb
Particulate Matter ($PM_{2.5}$)*	Fuel combustion (mobile sources, electric utilities, industrial processes), dust, agriculture, fires, and formation in the atmosphere due to chemical reactions	0 to 40 μg/m^3 (100 to 1,000 μg/m^3 near wildfires)
Particulate Matter (PM_{10})*	Dust (e.g., agriculture, roads, construction), brake/tire and engine wear from mobile sources, and fires	0 to 100 μg/m^3 (500 to 1,000+ μg/m^3 in dust storms)
Sulfur Dioxide (SO_2)*	Fuel combustion from electric utilities, refineries, and industrial processes	0 to 100 ppb (100 to 5,000 ppb near active volcanoes)
Ultrafine Particles (UFP)	Fuel combustion (mobile sources, industries), gasoline evaporation, and solvent usage	3,000 to 200,000 particles/cubic centimeter (cm^3)
Volatile Organic Compounds (VOCs)	Fuel combustion (mobile sources, industries), gasoline evaporation, solvents, and consumer products	5 to 100 μg/m^3

*Criteria pollutant regulated by the U.S. EPA (see Section 2.4)

> **What are mobile sources?**
>
> Mobile sources include vehicles on the road (i.e., on-road) like motorcycles, passenger cars and trucks, and commercial trucks and buses. Mobile sources also include vehicles not on roads (i.e., non-road) like excavators, aircraft, locomotives, marine vessels, other heavy equipment, recreation vehicles (e.g., snowmobiles, all-terrain vehicles), and small engines and tools (e.g., lawnmowers).

VOCs are not a single gas species but are comprised of thousands of chemicals. Total VOC (tVOC) measurement is an estimated concentration of several different VOC species. VOCs are commonly found in commercial products (e.g., paints, refrigerants, fuels), consumer products (e.g., cleaning supplies, deodorants, hair products), and used in industrial processes (e.g., chemical production, petroleum refining, fuel combustion) that evaporate into the air. VOCs occur indoors and outdoors. Some common VOCs include:

- **Benzene, Toluene, Ethylbenzene, and Xylene (BTEX)** are four VOCs that are normally grouped as they are often found together. The primary sources of BTEX are on-road and non-road gasoline vehicles and engines, petroleum transport/storage, and solvent usage.
- **Biogenic VOCs** are emissions created by some type of biological activity. Examples include emissions resulting from trees, vegetation, and microbial activity in soils. Emissions from biogenic sources can react in the atmosphere to form O_3 and PM pollutants.
- **Formaldehyde** is a colorless, flammable gas at room temperature that has a strong odor. Formaldehyde is a byproduct of combustion (e.g., emission gas stoves, kerosene space heaters, cigarette smoke). Some commercial products (e.g., glues, paints, building materials) also release formaldehyde.

Sometimes, concerns about new and emerging pollutants arise as researchers and scientists identify links with adverse health effects or environmental impacts. Some examples of emerging pollutants include:

- **Black carbon (BC)** is a type of particle produced from incomplete combustion and is emitted from sources such as diesel engines and wildfires. BC is almost entirely made of carbon and is strongly light absorbing. BC absorbs solar radiation and may lead to heating in the atmosphere (i.e., radiative forcing).
- **Methane (CH_4)**, the simplest hydrocarbon consisting of one carbon atom and four hydrogen atoms, accounts for approximately 10 percent of all U.S. greenhouse gas emissions from human activities, including leaks from natural gas systems and raising of livestock.

- **Polycyclic aromatic hydrocarbons (PAHs)** are a class of chemicals that occur naturally in coal, crude oil, and gasoline and diesel fuel. They are also produced by combustion of coal, oil, gas, wood, garbage, and tobacco, and by high-temperature cooking of meat and other foods. PAHs are a concern because they persist in the environment for long periods of time.

What are the Typical Characteristics of Traffic Emissions?

Pollutants directly emitted from cars, trucks and other mobile sources are found in higher concentrations near major roads. Examples of directly emitted pollutants include PM, CO, oxides of nitrogen (NO_x), and benzene, though hundreds of chemicals are emitted by motor vehicles. Motor sources also emit compounds that lead to the formation of other pollutants in the atmosphere, such as NO_2, which is found in elevated concentrations near major roads, and O_3, which forms further downwind. Beyond vehicle tailpipe and evaporative emissions, roadway traffic also emits brake and tire debris and can throw road dust into the air. Individually and in combination, many of the pollutants found near roadways have been associated with adverse health effects.

2.1.1 The Pollutant Lifecycle

After being emitted from a natural or anthropogenic source, air pollutants are transported in the atmosphere and can ultimately impact the environment and human population, as shown in Figure 2-6. Many processes throughout this lifecycle can make it challenging to understand pollution and its sources. While in the atmosphere, pollutants can undergo chemical reactions with other gases and particles. Atmospheric conditions can affect these chemical reactions (e.g., sunlight is needed to create O_3) and weather controls the movement and dispersion of pollutants from upwind locations (where air moves through before it goes over an area of interest) to downwind locations (where air goes after moving over an area of interest). Local geography can channel and direct the air pollutants to locations that can impact people and the environment. Eventually pollutants are removed from the atmosphere by deposition onto earth's surface or as people breathe in pollution. One of the biggest challenges in air quality monitoring is determining the origin of a measured pollutant, which requires an understanding of all factors—weather, atmospheric chemistry, and geography—that affected the pollutants on their journey from the original source to the measurement location.

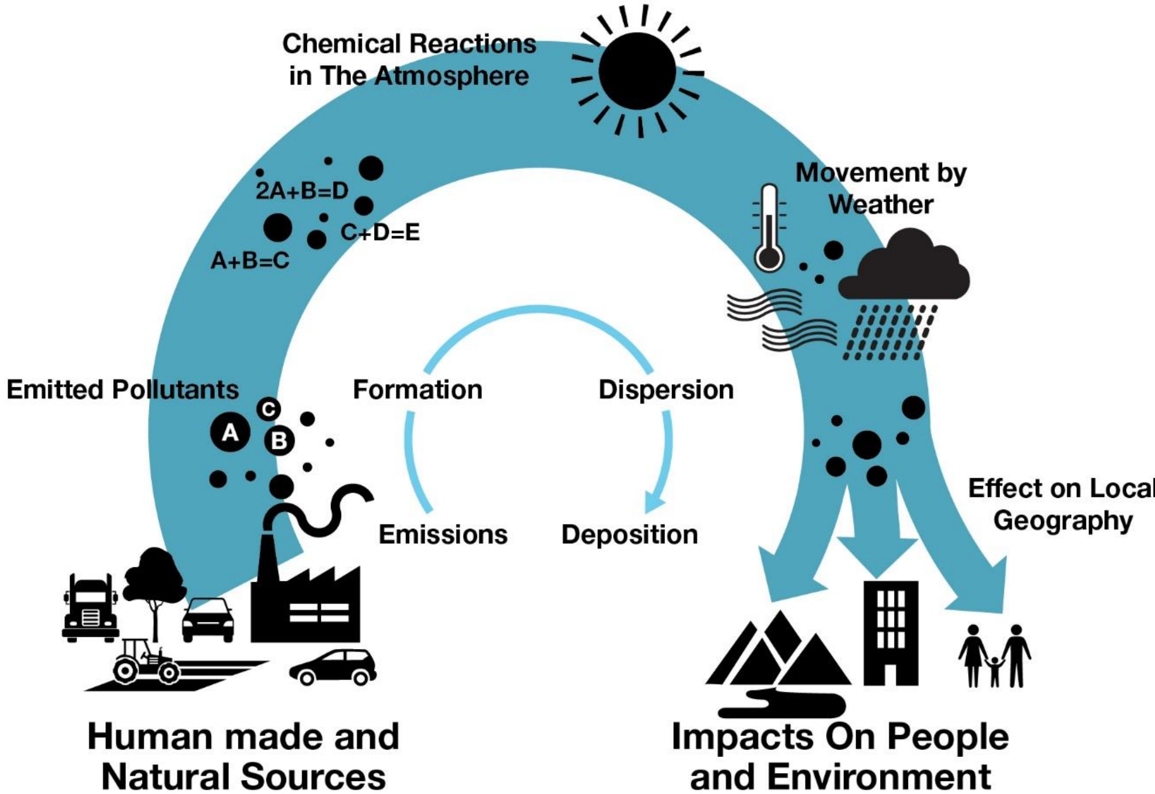


Figure 2-6. The Pollutant Lifecycle from Source to Impact on People and the Environment

2.1.2 Differences in Pollutant Concentrations Over Time

Pollutant concentrations may vary significantly depending on the time of day, day of the week, and season. These differences can be attributed to changes in emissions patterns, atmospheric conditions (e.g., mixing height, temperature, sunlight), the source's activity schedule (e.g., daily traffic rush hour patterns), and chemical reactions.

As shown in Figure 2-7, O_3 typically varies slowly on an hour-to-hour basis but often undergoes a diurnal change (i.e., daily cycle) from low concentrations at night to higher concentrations during the day. The day-to-day difference in emissions of O_3 precursors (e.g., vehicle emissions) can produce lower O_3 concentrations on weekends than weekdays. As sunlight and heat help convert emissions into O_3, concentrations are usually higher during summer.

$PM_{2.5}$ can change more rapidly on an hour-to-hour basis, even on a minute-to-minute basis, due to local sources and atmospheric conditions (see Figure 2-7 and Figure 2-3). $PM_{2.5}$ concentrations are generally higher at night and in the morning due to calm winds and pollution trapped below a nighttime temperature inversion. From day to day, $PM_{2.5}$ concentrations can build up and then change rapidly due to increasing winds or air mass changes (e.g., cold front passage). Lastly, $PM_{2.5}$ concentrations can vary based on season. For instance, wintertime concentrations may be high due to residential wood-burning activities in cold climates. Summertime concentrations may be high due to secondary particle formation in the Southeast U.S., seasonal crop burning, agricultural activities, or wildfire smoke.

Tip: Consider variations in pollutant concentrations when developing an air monitoring plan

Knowing the daily, weekly, and seasonal variations in pollutant concentrations can help you develop a plan for conducting air monitoring. This information can help guide the time and conditions under which measurements should be taken. See Chapter 3 for more information on monitoring using air sensors.

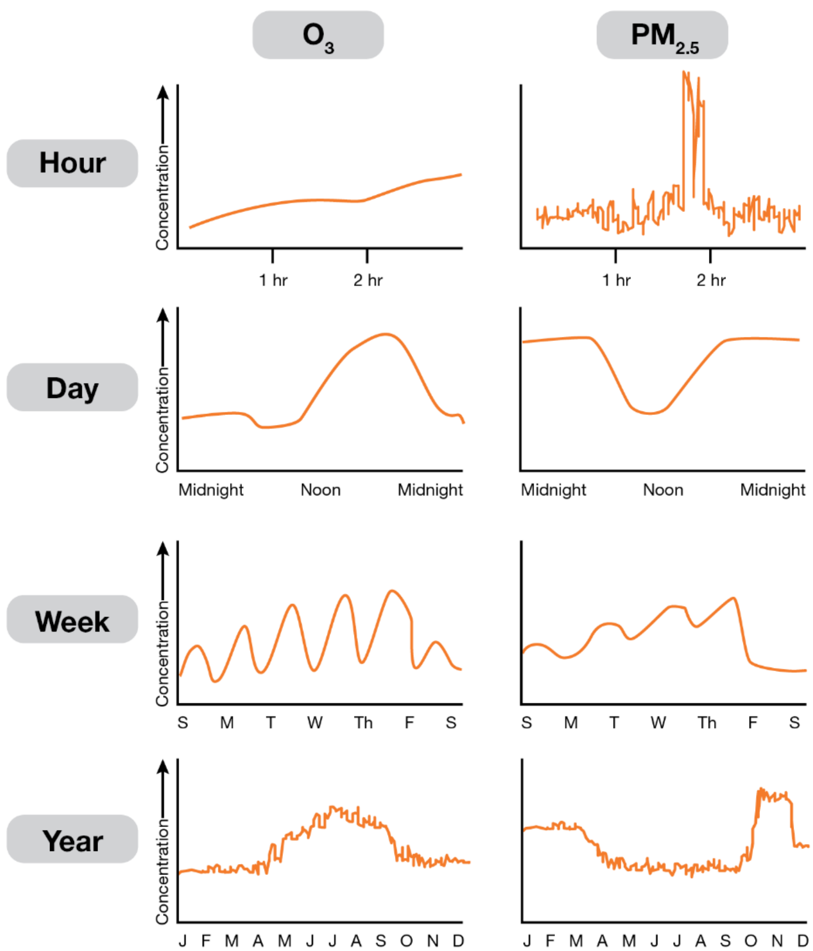


Figure 2-7. Typical Concentrations for O_3 and $PM_{2.5}$ During Different Time Periods

Resources for More Information

- **U.S. EPA Air Quality Planning and Standards Website**
  - Provides additional information regarding air quality and pollutants
  - https://www3.epa.gov/airquality/

- **U.S. EPA National Air Quality – Status and Trends of Key Air Pollutants Website**
  - Provides air quality trends, reports, and summaries for criteria air pollutants
  - https://www.epa.gov/air-trends

- **U.S. EPA AirNow Website**
  - Provides a variety of resources on air quality including air quality information at local, state, national, and world views, air quality and health, maps and data, educational resources, and more
  - https://www.airnow.gov/

- **Wildfire Smoke: A Guide for Public Health Officials,** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-452/R-19-901, August 2019
  - Document provides guidance to tribal, state, and local public health officials, and other interested groups (e.g., health professionals, air quality officials, public) in preparing for wildfire smoke events and in communicating health risks and taking measures to protect the public during smoke events
  - https://www.airnow.gov/sites/default/files/2021-05/wildfire-smoke-guide-revised-2019.pdf

- **U.S. EPA Mobile Source Pollution and Related Health Effects Website**
  - Overviews mobile sources of air pollution, summarizes health effects associated with exposure to mobile source emissions, provides data and modeling resources, and information on programs to reduce mobile source pollution
  - https://www.epa.gov/mobile-source-pollution

- **U.S. EPA Near-Roadway and Other Near-Source Pollution Website**
  - Overview of research on near-roadway pollution from cars, trucks, and other mobile sources and frequently asked questions about near-roadway air pollution and health effects
  - https://www.epa.gov/air-research/research-near-roadway-and-other-near-source-air-pollution

- **Near-Roadway Air Pollution and Health: Frequently Asked Questions,** U.S. Environmental Protection Agency, Office of Transportation and Air Quality, EPA-420-F-14-044, August 2014
  - Document provides U.S. EPA's responses to frequently asked questions received from the public regarding exposure to near-roadway air pollution
  - https://nepis.epa.gov/Exe/ZyPDF.cgi/P100NFFD.PDF?Dockey=P100NFFD.PDF

- **Report to Congress on Black Carbon,** U.S. Environmental Protection Agency, EPA-450/R-12-001, March 2012
  - Document summarizes available scientific information on the current and future impacts of black carbon (BC) and evaluates the effectiveness of available BC mitigation approaches and technologies
  - https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100EIJZ.txt

- **U.S. EPA Integrated Science Assessments (ISAs) for Criteria Air Pollutants Website**
  - Reports that summarize scientific information that is the foundation for reviewing the National Ambient Air Quality Standards (NAAQS) for criteria pollutants; ISAs are an important resource for state and local health agencies, other federal agencies, and international health organizations
  - https://www.epa.gov/isa

2.2 Pollutant Effects on Health and the Environment

A broad range of health and environmental effects have been observed following exposure to air pollutants or mixtures of air pollutants. Health effects vary by the type of pollutant or mixture of pollutants, concentration, and exposure time, which can be short term (hours to weeks) or long term (months to years). 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 other effects. Table 2-2, provided by EPA's Office of Air Quality Planning and Standards Health and Environmental Impacts Division, summarizes the health and environmental effects of common air pollutants.

Table 2-2. Health and Environmental Effects of Select Common Air Pollutants

Pollutant	Health Effects	Environmental Effects
Ammonia (NH_3)	• Can cause severe irritation of the skin, eyes, nose, and throat	• Precursor to secondary particulate formation • Contributes to acid deposition of soils and surface waters
Benzene, Toluene, Ethylbenzene,	• Known human carcinogen • Short-term exposure can cause drowsiness, dizziness, headaches,	• Can contribute to formation of ground-level O_3

Pollutant	Health Effects	Environmental Effects
and Xylene (BTEX)	and irritation to the eyes, skin, and respiratory tract • Long-term exposure can cause blood disorders and adverse effects to the reproductive system	
Black Carbon (BC)	• A component of PM (see health effects of PM)	• A component of PM (see environmental effects of PM) • Contributes to climate change causing changes in patterns of rain and clouds • As BC deposits in the Arctic, the particles cover the snow and ice, decreasing the Earth's ability to reflect warming rays of the sun, while absorbing heat and hastening melting
Carbon Monoxide (CO)	• Breathing air with a high concentration reduces the amount of oxygen that can be transported in the blood stream to critical organs like the heart and brain • At very high levels, which are possible indoors or in other enclosed environments, CO can cause dizziness, confusion, unconsciousness, and death • Short-term exposure to elevated CO may result in reduced oxygen to the heart accompanied by chest pain (also known as angina)	• There is no secondary standard as the concentrations that would have any effect on flora or fauna are many times higher than what might occur in outdoor air
Ground-level Ozone (O_3)	• Elevated concentrations cause respiratory effects and can: ○ Trigger responses such as throat irritation or burning sensation in the airways, coughing, difficulty breathing, and airway inflammation ○ Reduce lung function and harm lung tissue ○ Aggravate bronchitis, emphysema, and asthma, increasing the risk of asthma attacks and associated outcomes in affected individuals	• Elevated concentrations can: ○ Affect sensitive vegetation and ecosystems, including in parks and wilderness areas, by reducing photosynthesis and slowing growth ○ Increase sensitive plants' risk from other stressors such as disease or insects ○ Cause blemishes or stippling on leaves of sensitive plants • O_3 is a greenhouse gas, with associated potential for effects on climate
Lead (Pb)	• Elevated exposures can adversely affect the nervous system, kidney function, immune system, reproductive and developmental systems, and the cardiovascular system • Elevated exposure can also affect the oxygen carrying capacity of the blood • The effects most likely to be encountered in current populations are neurological effects in children. Infants and young children are especially sensitive to lead	• Elevated Pb in the environment can result in effects on: ○ Terrestrial and aquatic animal behavior, reproduction, development, and survival ○ Plant growth

Pollutant	Health Effects	Environmental Effects
	exposures, which may contribute to behavioral problems, learning deficits, and lowered intelligence quotient (IQ)	
Mercury (Hg)	• Exposure to methylmercury (MeHg) occurs when people eat fish and fish products with high levels of MeHg • The primary effect is damage to the central nervous system: o At very high exposures, symptoms may include blurred vision, malaise, speech difficulties, and constriction of the visual field o For infants born to pregnant people with high levels of methylmercury, effects such as mental retardation, ataxia, constriction of the visual field, blindness, and cerebral palsy. At lower MeHg concentrations, effects such as developmental delays and abnormal reflexes	• Deposits to soil and bodies of water • MeHg can accumulate in fish which are then consumed by birds, mammals, and predators and, at very high concentrations, cause effects in animals that include: o Death o Reduced reproduction o Slower growth and development o Abnormal behavior
Methane (CH_4)	• Not generally considered a toxic gas • Very high exposures can cause headaches, dizziness, nausea, vomiting, and, in severe cases, respiratory problems and loss of consciousness	• Greenhouse gas that contributes to climate change, particularly warming of the Earth
Nitrogen Dioxide (NO_2)	• Exposure to high concentrations of NO_2 can irritate airways in the respiratory system • Exposure to elevated concentrations over short periods of time can aggravate respiratory diseases, particularly asthma, leading to respiratory symptoms (e.g., coughing, wheezing, difficulty breathing) • Longer exposures to elevated concentrations may contribute to the development of asthma and potentially increase susceptibility to respiratory infections • Contributes to the formation of ground-level O_3 and PM (see health effects of PM)	• NO_2 and other oxides of nitrogen (NO_x) interact with water, oxygen, and other chemicals in the atmosphere to form acid rain, which can harm sensitive ecosystems such as lakes and forests • Can contribute to nutrient pollution in coastal waters • Contributes to the formation of ground-level O_3 and PM (see environmental effects of PM)

Pollutant	Health Effects	Environmental Effects
Particulate Matter ($PM_{2.5}$ and PM_{10})	• Exposure can affect both the lungs and the heart. Numerous scientific studies have linked particle pollution to a variety of problems, including: ○ Premature death in people with heart or lung disease ○ Nonfatal heart attacks ○ Irregular heartbeat ○ Aggravated asthma ○ Decreased lung function ○ Increased respiratory symptoms, such as irritation of the airways, coughing, or difficulty breathing	• Can reduce visibility (create haze) • Can be carried over long distances by wind and then settle on ground or water. Depending on its chemical composition, the effects of this settling may include: ○ Acid rain-like effects, such as making lakes and streams acidic ○ Effects on the nutrient balance in coastal waters and large river basins or in soils, with related effects on sensitive forests, ecosystems, and farm crops • Can have effects on climate, including radiative forcing • Can stain and damage stone and other materials
Sulfur Dioxide (SO_2)	• Short-term exposure to elevated concentrations can harm the respiratory system and make breathing difficult • Contributes to the formation of PM (see health effects of PM)	• At high concentrations, gaseous sulfur oxides (SO_X) can harm trees and plants by damaging foliage and decreasing growth • SO_2 and other SO_x interact with water, oxygen, and other chemicals in the atmosphere to form acid rain, which can harm sensitive ecosystems such as lakes and forests • Contributes to the formation of PM (see environmental effects of PM)
Ultrafine Particles (UFP)	• Included in $PM_{2.5}$ mass (see health effects of PM) • There is some evidence associated with respiratory, cardiovascular, and nervous system effects, but research on UFP-associated health effects is still emerging	• Included in $PM_{2.5}$ mass (see environmental effects of PM)
Volatile Organic Compounds (VOCs)	• Some are air toxic pollutants that cause cancer and/or other serious health effects • Contributes to the formation of ground-level O_3 and PM (see health effects of PM)	• Contributes to the formation of ground-level O_3 and PM (see environmental effects of PM)

Resources for More Information

- **U.S. EPA Criteria Air Pollutants Website**
  - Provides detailed information on the six criteria pollutants including basic information, health and environmental effects, technical documents, setting and reviewing the standards, implementing the standards, and current air quality designations
  - https://www.epa.gov/criteria-air-pollutants

- **Health Effects of Ozone (O_3) Pollution Website**
  - Provides detailed information on health effects of breathing air containing O_3
  - https://www.epa.gov/ground-level-ozone-pollution/health-effects-ozone-pollution

- **Health and Environmental Effects of Particulate Matter (PM) Website**
  - Provides detailed information on health and environmental effects of PM
  - https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

- **Basic Information about Nitrogen Dioxide (NO_2) Website**
  - Provides basic information on NO_2 including health and environmental effects
  - https://www.epa.gov/no2-pollution/basic-information-about-no2#Effects

- **Basic Information about Sulfur Dioxide (SO_2) Website**
  - Provides basic information on SO_2 including health and environmental effects
  - https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects

- **Basic Information about Carbon Monoxide (CO) Outdoor Air Pollution Website**
  - Provides basic information on CO including health and environmental effects
  - https://www.epa.gov/co-pollution/basic-information-about-carbon-monoxide-co-outdoor-air-pollution#Effects

- **Basic Information about Lead (Pb) Air Pollution Website**
  - Provides basic information on Pb including health and environmental effects
  - https://www.epa.gov/co-pollution/basic-information-about-carbon-monoxide-co-outdoor-air-pollution#Effects

- **Report on the Environment – Volatile Organic Compounds (VOCs) Emissions Website**
  - Provides detailed information on sources, health and environmental effects, and emissions estimates of VOCs
  - https://cfpub.epa.gov/roe/indicator.cfm?i=23#1

- **Definition of VOC Website**
  - Provides a detailed information on the definition of VOCs as outlined in air pollution regulations
  - https://www.epa.gov/air-emissions-inventories/what-definition-voc

- **Health Effects of Exposures to Mercury Website**
  - Provides detailed information on health effects of exposure to mercury
  - https://www.epa.gov/mercury/health-effects-exposures-mercury

- **Integrated Risk Information System (IRIS) Methylmercury (MeHg) Summary Website**
    - Provides health assessment information on MeHg based on review of toxicity data
    - https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=73

- **Agency for Toxic Substances and Disease Registry (ATSDR) Public Health Statement for Benzene Website**
    - Provides information about benzene and effects of exposure to it
    - https://wwwn.cdc.gov/TSP/PHS/PHS.aspx?phsid=37&toxid=14

- **Integrated Risk Information System (IRIS) Benzene Summary Website**
    - Provides health assessment information on benzene based on review of toxicity data
    - https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=276

- **Global Methane Initiative (GMI) Website**
    - Provides information on GMI, description of methane and mitigation approaches, methane sites around the globe, and more
    - https://www.epa.gov/gmi

- **Report to Congress on Black Carbon**, U.S. Environmental Protection Agency, EPA-450/R-12-001, March 2012
    - Report provides summary on black carbon, health and environmental effects, emissions, mitigation overview, and more
    - https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100EIJZ.txt

- **Integrated Science Assessment (ISA) for Particulate Matter**, U.S. Environmental Protection Agency, EPA/600/R-19/188, December 2019
    - ISA provides detailed information on particulate matter including sources, ambient levels, health and environmental effects, and more
    - https://www.epa.gov/isa/integrated-science-assessment-isa-particulate-matter

- **Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects**, HEI Panel on the Health Effects of Traffic-Related Air Pollution, HEI Special Report 17, Health Effects Institute (HEI), January 2010
    - Report provides a summary and synthesis of information on air pollution from traffic and its health effects
    - https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health

2.3 Outdoor Air Pollution Monitoring

Air pollution monitoring is the detection of pollutant levels by measuring the quantity and types of certain pollutants in the outdoor air. Different methods and instruments are used to measure pollutants and it is critical to match a specific application's measurement needs with a device that provides sufficient accuracy, reliability, and traceability.

Some common measurement approaches for monitoring air quality from fixed locations and mobile platforms (e.g., a vehicle) are shown in Figure 2-8. Several categories of measurement methods are described in more detail below.

- **Reference monitors** are used to determine compliance with the National Ambient Air Quality Standards (NAAQS; *see Section 2.4*) and are designated as either Federal Reference Method (FRM) or Federal Equivalent Method (FEM) monitors. These monitors must meet strict operating and performance requirements, as outlined in the U.S. Code of Federal Regulations (40 CFR Parts 50, 53, and Part 58). Reference monitors produce very high quality, accurate data. PM FRM samplers collect particles on a filter over a period of time (typically 24 hours), whereas continuous FEM monitors detect pollutant concentrations on a more frequent basis (e.g., continuously every hour). See the U.S. EPA's Ambient Monitoring Technology Information Center (AMTIC) for a list of designated FRM/FEM monitors. Precise operation, siting, and quality assurance and quality control (QA/QC) are necessary to ensure that reference monitors produce accurate data.
- **Research instruments** describe a wide range of technologies ranging from lower-cost air sensor technologies to mid-range prototype instruments to high-end laboratory-type instruments modified for use in the field. These instruments are often built or designed for specific applications. They may be designed to explore a specific research question or as prototypes designed to measure pollutants that do not have an existing measurement method. These instruments are most often operated by experts to achieve the performance needs for their application. After demonstrating strong comparability with FRM/FEM instruments, they can be used as a reference monitor if/when it is not feasible to deploy an FRM/FEM. For example, an instrument like an E-BAM may be considered a near-reference instrument because it has comparable performance to FRM/FEM instruments, but it is designed to be operated outdoors and designed to be portable so that it can be quickly deployed to measure wildfire smoke in more rugged terrain. It does not have an FEM designation, but has many of the features of an FEM, and when operated by trained staff can provide valuable data for this application.
- **Remote sensing** is a method for measuring pollutants at a distance without physical contact (e.g., by measuring reflected or emitted light). Remote sensing can be useful for detecting PM, gaseous criteria pollutants, and some VOCs. Remote sensing can be deployed aboard aircraft, satellite-based platforms in orbit, or at ground-based sites.

- **Air sensors** are a class of technology that are lower in cost, more portable, and generally easier to operate than reference monitors or research instruments. Air sensors can measure some, but not all, air pollutants including PM and gases. However, the accuracy, lifetime, and reliability of sensors varies due to the underlying measurement technology, quality of different air sensor components, environmental conditions, and methods of operation. Table 2-3 summarizes the main differences between air sensors and reference monitors.

	Reference *(Certified)* Sampler	Reference *(Certified)* Continuous	Remote Sensing Ground-based	Remote Sensing Space-based	Air Sensor
Accuracy	High	High	High	Varies	Varies
Complexity	High	High	High	High	Low
Measurement Frequency	Daily	Sub hourly to hourly	Sub hourly	Hourly to Daily	Sub hourly
Relative Cost	**$$**	**$$$**	**$$$$**	**$$$**	**$**

Figure 2-8. Common Types of Air Monitoring Instruments and Their Characteristics

Table 2-3. Comparison Between Reference Monitors and Air Sensors

Consideration	Reference Monitors	Air Sensors
Typical Purchase Cost	$15,000 to $40,000 (U.S. Dollars)	$100 to $5,000 (U.S. Dollars)
Staff Training for Operation	Highly trained technical staff	Little or no training (user guide/manual may help)
Operating Expense	Expensive – need for shelter, technical staff, maintenance, repair, quality assurance	Less expensive – need for device replacement or repair, data streaming, data management
Siting Location	Fixed location (building/trailer needed)	More portable (with basic weather protection)
Data Quality	Known and consistent quality in a variety of conditions	Unknown and may vary from sensor to sensor in different weather conditions and pollution environments
Operating Lifetime	10 years or more (calibrated and operated to maintain accuracy)	Short (pollutant dependent; <1-3 years) (may become less accurate over time)
Used for Regulatory Monitoring	Yes	No

The concentration of many pollutants varies over long or even short distances, therefore deciding where to place instruments is very important. The location of where pollutants are measured determines what is measured. As shown in Figure 2-9, air monitoring can occur in different locations and represent different conditions.

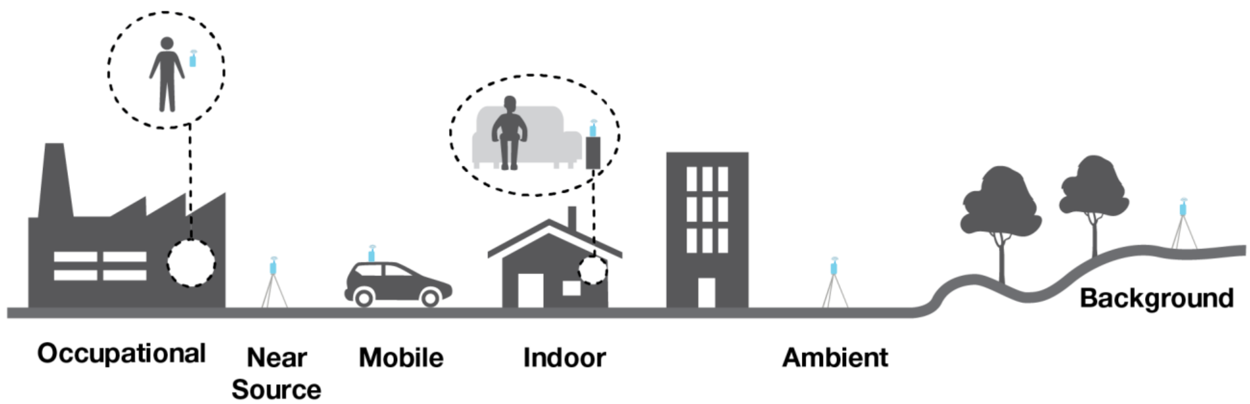


Figure 2-9. Different Air Monitoring Locations for Outdoor Air (Near Source, Mobile, Ambient, and Background) and Indoor Air (Occupational and Residential)

Concentrations for most pollutants will almost always be highest near the source, decreasing rapidly within the first few hundred feet away from the source. If multiple sources are widely distributed within a given area, pollutant concentrations may be more similar, but will still be different from location to location. Other factors, including geography and local atmospheric conditions will also influence concentrations.

Tip: Carefully consider where to locate air sensors when conducting an air monitoring study

Carefully locating an air sensor will play a significant role in determining whether the data collected represent the location and are useful. Section 3.5 provides further discussion regarding where and how to properly place air sensor devices.

An **air pollution monitoring network** is a collection of sites equipped with instrumentation for measuring one or more pollutants. Monitoring networks are designed and operated for specific purposes and objectives and use instruments that can meet the goals necessary for the objective (e.g., use of FRM or FEM for monitoring the NAAQS as required by the Clean Air Act, CAA) because of the stringent needs for accuracy and completeness. U.S. EPA's AirData Air Quality Monitors website (Figure 2-10) provides an interactive display of air monitoring locations and monitor-specific information for the different regulatory air monitoring networks using the AirData Map.

Tip: You can access outdoor air monitoring data in several ways

Current conditions and forecast data are available through AirNow.gov. Historical data are available as pre-generated data files, through the AQS API, or through AirData reports and visualizations.

Within the United States (U.S.), Puerto Rico, and the U.S. Virgin Islands, ambient (outdoor) concentrations of criteria air pollutants are measured at more than 4,000 monitoring stations owned and operated by tribal, state, local, or environmental agencies. Each of these sites measures one or more of the criteria air pollutants [O_3, PM ($PM_{2.5}$ and PM_{10}), CO, NO_2, SO_2, Pb] using instruments that have been designated as FRMs or FEMs. In managing these instruments, agencies follow stringent siting criteria, extensive operational plans, and quality assurance procedures (e.g., calibration, maintenance, audits, data validation) to ensure that they produce high quality data. EPA's QA Handbook further describes these procedures. Agencies send quality assured hourly or daily measurements of pollutant concentrations to EPA's database called the Air Quality System (AQS). AirData retrieves the air quality data from AQS and provides the public with easy access to daily and annual data summaries.

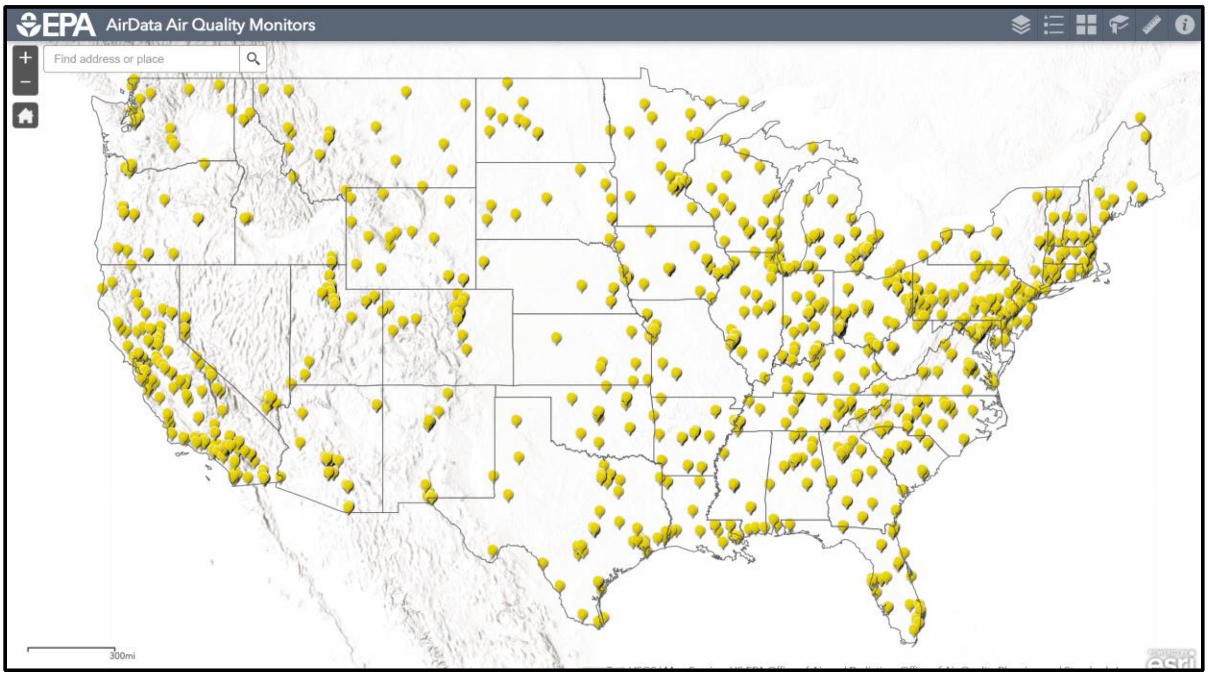


Figure 2-10. U.S. EPA's AirData Air Quality Monitors website – Active $PM_{2.5}$ Continuous Monitoring Stations (as of 9/30/2022)

Several other air monitoring networks serving other needs also exist within the U.S. including

- **National Air Toxics Trends Stations (NATTS)** which are set up across the U.S. to monitor air toxics. Under the Clean Air Act (CAA), U.S. EPA regulates a list of 187 hazardous air pollutants (HAPs), also called air toxics. The principal objective of the NATTS network is to provide long-term monitoring data across representative areas of the country to establish overall trends for priority pollutants such as benzene, formaldehyde, 1,3-butadiene, hexavalent chromium, PAHs, and others.

- The **Interagency Monitoring of Protected Visual Environments (IMPROVE)** monitoring program which was initiated in response to the CAA and Regional Haze Rule to establish current visibility and aerosol conditions, identify chemical species and anthropogenic emission sources responsible for visibility impairment, and document long-term trends for assessing progress toward visibility goals for national parks and wilderness areas. The IMPROVE network uses identical reference samplers to collect 24-hour PM filters every three days that are analyzed for chemical components in PM.
- The **Chemical Speciation Network (CSN)** which collects $PM_{2.5}$ filter samples that are analyzed for chemical components in PM (e.g., metals, ions, carbon). These data are collected to assess trends, link health effects to $PM_{2.5}$ constituents, characterize annual and seasonal spatial variation of $PM_{2.5}$, and other applications.
- The **National Core Multipollutant Monitoring Network** (**NCore)** which is a network that integrates several advanced measurement systems for PM, gaseous pollutants, and meteorology. NCore sites collect data to track long-term trends, support long-term health assessments, support scientific studies, and other applications.

Resources for More Information

- **U.S. EPA Ambient Monitoring Technology Information Center (AMTIC) Website**
  - Contains technical information regarding ambient air monitoring programs, including the networks of state and local air monitoring stations (SLAMS), monitoring methods, and QA/QC procedures
  - https://www.epa.gov/amtic

- **U.S. EPA Ambient Air Monitoring Website**
  - Overviews the reasons for why monitoring ambient air quality is important and provides links to U.S. EPA's AMTIC, Air Quality System (AQS), Air Data, AirNow, and AirNow International websites
  - https://www.epa.gov/air-quality-management-process/managing-air-quality-ambient-air-monitoring

- **Overview of the Clean Air Act (CAA) Website**
  - Provides an in-depth overview of the CAA including history and requirements, role of science and technology, role of state, local, tribal and federal government, and more
  - https://www.epa.gov/clean-air-act-overview

- **Videos on Sources of Air Quality Information and Air Sensor Measurements, Data Quality, and Interpretation**
    - Educational videos, in both English and Spanish, that can be used to learn how U.S. EPA collects and uses air quality data, how air quality health risks are communicated, and how to interpret data collected using air sensors
    - https://www.epa.gov/air-sensor-toolbox/videos-air-sensor-measurements-data-quality-and-interpretation

- **Understanding Air Quality and Monitoring Video**, South Coast Air Quality Management District (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC), September 2021
    - Educational video providing background on air quality, criteria pollutants, pollutant sources and health effects, air quality monitoring technologies, and the role of air sensors
    - https://www.youtube.com/watch?v=2r0XxQm50lE

- **California Air Resources Board (CARB) Outline of Measurement Technologies**
    - Online resource that discusses air monitoring applications, applicable measurement technologies, and their relative availability and cost developed by CARB to support community air monitoring conducted under California Assembly Bill 617
    - https://ww2.arb.ca.gov/capp-resource-center/community-air-monitoring/outline-of-measurement-technologies

- **Hazardous Air Pollutants (HAPs) Website**
    - Provides detailed information on HAPs including the list of HAPs, health an environmental effects, sources and exposures, data, and more
    - https://www.epa.gov/haps

- **Regional Haze Program Website**
    - Provides information on the Regional Haze Rule and Program, list of the national parks and wilderness areas covered by the program, and more
    - https://www.epa.gov/visibility/regional-haze-program

2.4 Air Quality Standards and Indices

Determining the health implications of air quality measurements is complex. Fortunately, there are ways to put air quality measurements into context. Government agencies conduct extensive analyses of the research on health effects of air pollutants (e.g., U.S. EPA's Integrated Science Assessments, the 2021 Air Quality in Europe report prepared by the European Union). This research and high-quality data are used to establish the standards and indices to protect public health. Many countries set their own air quality standards. In addition, the WHO has established air quality standards.

Major U.S. air quality standards and indices include:

- **National Ambient Air Quality Standards (NAAQS).** The CAA, which was last amended in 1990, requires the U.S. EPA to set NAAQS for air pollutants considered harmful to public health and the environment. The CAA identifies two types of NAAQS: primary and secondary standards. Primary standards provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings. The U.S. EPA has set NAAQS for six principal pollutants, called **criteria air pollutants**: PM ($PM_{2.5}$ and PM_{10}), O_3, CO, SO_2, NO_2, and Pb. As required by the CAA, the U.S. EPA reviews and revises the standards, if appropriate, every 5 years. The NAAQS are summarized in Table 2-4.

Why Aren't there NAAQS for all Air Pollutants?

Other common air pollutants shown in Table 2-1 (e.g., CH_4, VOCs, benzene, Hg, NH_3, BC, UFP) are not criteria pollutants; therefore, the U.S. EPA has not established NAAQS for these pollutants.

- **Air Quality Index (AQI).** The AQI was established by the U.S. EPA as a method to translate pollution measurements into potential health effects. The AQI is a numeric scale for reporting air quality that describes how clean or polluted the air is at a given location, and any associated health effects that may result from exposure to the air. Section 2.5 and Appendix D provide more information on the AQI and how it is calculated.
- **National Institute for Occupational Safety and Health (NIOSH)**. NIOSH has established guidelines and recommendations for preventing work-related injury and illness, including exposure to air pollutants. In general, these guidelines often represent shorter time periods because they relate to occupational locations and schedules (e.g., workdays).

How are NAAQS and NIOSH Guidelines Different?

NIOSH guidelines are established for some of the pollutants shown in Table 2-1 and some additional pollutants as well. NIOSH concentration levels are different than the NAAQS because they are established for occupational exposures only.

Table 2-4. U.S. EPA National Ambient Air Quality Standards (NAAQS; *current as of 9/30/2022*)

Air Pollutant	Primary or Secondary Standard*	Averaging Time	Concentration Level	Form**
Carbon Monoxide (CO)	Primary	8 hours	9 ppm	Not to be exceeded more than once per year
		1 hour	35 ppm	
Lead (Pb)	Primary and Secondary	Rolling 3 month average	0.15 $\mu g/m^3$	Not to be exceeded
Nitrogen Dioxide (NO_2)	Primary	1 hour	100 ppb	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	Primary and Secondary	1 year	53 ppb	Annual mean
Ozone (O_3)	Primary and Secondary	8 hours	70 ppb	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years
Particulate Matter ($PM_{2.5}$)	Primary	1 year	12.0 $\mu g/m^3$	Annual mean, averaged over 3 years
	Secondary	1 year	15.0 $\mu g/m^3$	Annual mean, averaged over 3 years
	Primary and Secondary	24 hours	35 $\mu g/m^3$	98th percentile, averaged over 3 years
Particulate Matter (PM_{10})	Primary and Secondary	24 hours	150 $\mu g/m^3$	Not to be exceeded more than once per year on average over 3 years
Sulfur Dioxide (SO_2)	Primary	1 hour	75 ppb	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	Secondary	3 hours	0.5 ppm	Not to be exceeded more than once per year

*The *primary standard* provides public health protection, including protecting the health of sensitive populations such as asthmatics, children, and the elderly. The *secondary standard* provides public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

**See the AQS data dictionary for the definitions and calculations of these forms.

In the U.S. only data from properly operated, cited, and maintained FRM and FEM instruments are used to determine compliance with the NAAQS. When comparing air quality measurements to these standards, it is important to ensure that the measurements align with the standard. Every standard has an associated concentration level for a specified averaging time period (e.g., 1 hour, 24 hours, 1 year) and a location (e.g., ambient, occupational). For example, Table 2-4 shows the related averaging time period, and concentration level for each criteria air pollutant for the NAAQS.

How Can I Compare Air Sensor Measurements to the NAAQS or AQI for Informational Purposes?

When comparing measurements from an air sensor to the NAAQS or AQI, it is important to remember that air sensors may over- or under-estimate pollutant concentrations (see *Section 3.6*). Therefore, sensor data must be cleaned and corrected and then averaged to match the time average specified for the pollutant and air quality standard or index. For example, to compare O_3 air sensor measurements provided every minute to the 8-hour NAAQS for O_3 of 70 ppb, you would need to clean and correct the O_3 sensor data and then calculate an 8-hour average from the 1-minute sensor measurements before comparing.

What Happens if an Air Pollutant Measurement is Above the NAAQS Concentration Level for the Specified Averaging Period?

Each NAAQS has a 'form' (see Table 2-4) which is a criterion for how many times the standard may be exceeded in a certain timeframe. Even though a measured concentration may exceed the NAAQS (called an **exceedance**), it does not constitute a NAAQS violation. So, what is a NAAQS **exceedance** vs. a NAAQS **violation**?

A NAAQS **exceedance** occurs when a measured concentration exceeds the concentration level for the averaging period specified by the NAAQS. For example, an exceedance of the short-term (24-hour) $PM_{2.5}$ NAAQS occurs when the $PM_{2.5}$ concentration measured at a regulatory air monitoring location is greater than 35 $\mu g/m^3$.

Air monitoring agencies must report NAAQS exceedances to the public.

A NAAQS **violation** occurs when a measured concentration level exceeds the concentration level for the specified NAAQS averaging period for specific criteria over a specified timeframe. For example:

A **violation** of the 24-hour $PM_{2.5}$ NAAQS occurs when the 3-year average of the annual 98^{th} percentile 24-hour concentration is greater than 35 $\mu g/m^3$

A **violation** of the 1-year $PM_{2.5}$ NAAQS occurs when the annual mean averaged over 3 years is greater than 12 $\mu g/m^3$

An area that has a NAAQS **violation** for any given criteria air pollutant, can potentially be designated as **nonattainment** (not meeting the NAAQS) for that pollutant and may need to address in State Implementation Plans (SIPs) how they will reach attainment.

- **WHO National Air Quality Standards Tool**
    - An interactive tool providing an international map of current national air quality standards for criteria pollutants for various averaging times
    - https://www.who.int/tools/air-quality-standards

- **Air Quality in Europe 2021**
    - An annual assessment of recent air quality trends at both European and national levels
    - https://www.eea.europa.eu//publications/air-quality-in-europe-2021

- **Air Quality System Data Dictionary**
    - The AQS Data Dictionary describes the fields typically encountered by AQS users and are listed in alphabetical order; field definitions and calculation algorithms are provided as appropriate
    - https://aqs.epa.gov/aqsweb/documents/AQS_Data_Dictionary.html

- **U.S. EPA National Ambient Air Quality Standards (NAAQS) Table**
    - A webpage detailing the NAAQS for six criteria pollutants which includes details from Table 2-4 but is a resource that will be updated if the standards change
    - https://www.epa.gov/criteria-air-pollutants/naaqs-table

- **The National Institute for Occupational Safety and Health (NIOSH)**
    - The Occupational Safety and Health Act of 1970 established NIOSH as a research agency focused on the study of worker safety and health, and empowering employers and workers to create safe and healthy workplaces
    - https://www.cdc.gov/niosh/index.htm

- **Center for Disease Control and Prevention (CDC) National Environmental Public Health Tracking – Air Quality**
    - CDC works closely with the U.S. Environmental Protection Agency, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Association (NOAA), and the National Weather Service to provide air quality data on the Tracking Network and to better understand how air pollution affects our health
    - https://www.cdc.gov/nceh/tracking/topics/AirQuality.htm

- **Greenbook: Nonattainment Areas for Criteria Pollutants**
    - The EPA Green Book provides detailed information about area National Ambient Air Quality Standards (NAAQS) designations, classifications and nonattainment status
    - https://www.epa.gov/green-book

2.5 The Air Quality Index (AQI)

As previously described, air pollution can have a number of serious health impacts. For all criteria pollutants except Pb, U.S. EPA has established the AQI. The AQI scale runs from 0 to 500, with higher AQI values indicating greater levels of air pollution and associated health concerns (Table 2-5). For example, an AQI value of 50 or below represents “Good” air quality, while an AQI value over 300 represents “Hazardous” air quality.

Table 2-5. The Air Quality Index (AQI) Levels of Health Concern, Numerical Values, and Meanings

Daily AQI Color	Levels of Concern	Values of Index	Description of Air Quality
Green	Good	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk.
Yellow	Moderate	51 to 100	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Orange	Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Red	Unhealthy	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Purple	Very Unhealthy	201 to 300	Health alert: The risk of health effects is increased for everyone.
Maroon	Hazardous	301 and higher	Health warning of emergency conditions: everyone is more likely to be affected.

The AQI is divided into six color-coded categories, as shown in Table 2-5, with each category corresponding to a different level of health concern. The color coding allows the public to quickly determine whether air quality is reaching unhealthy levels in their communities. The specific concentration breakpoints for each of the six levels vary by pollutant.

For each pollutant, an AQI value of 100 generally corresponds to an ambient air concentration equal to the level of the short-term NAAQS for protection of public health. AQI values at or below 100 are generally considered to be satisfactory. AQI values above 100 are considered to be unhealthy for sensitive groups of people (see Table 2-6), then unhealthy for everyone as AQI values reach higher levels.

Table 2-6. Pollutant-Specific Sensitive Groups for the AQI Greater than 100 (*Additional information available on the AirNow website*)

<table>
<tr><th>Pollutant</th><th>At-Risk Populations</th></tr>
<tr><td>Carbon Monoxide (CO)</td><td>People with heart disease</td></tr>
<tr><td>Nitrogen Dioxide (NO_2)</td><td>People with asthma, children, and older adults</td></tr>
<tr><td>Ozone (O_3)</td><td>People with lung disease, children and teenagers, older adults, people who are active outdoors (including outdoor workers), people with certain genetic variants, and people with diets limited in certain nutrients</td></tr>
<tr><td>Particulate Matter ($PM_{2.5}$)</td><td rowspan="2">People with heart or lung disease, older adults, children, and people of low socioeconomic status</td></tr>
<tr><td>Particulate Matter (PM_{10})</td></tr>
<tr><td>Sulfur Dioxide (SO_2)</td><td>People with asthma, children, and older adults</td></tr>
</table>

U.S. EPA calculates the AQI values based on air pollution data that is averaged over 1, 8, or 24 hours, depending on the pollutant (see Table 2-4). The reason for the different averaging times is that different pollutants affect the human body in different ways. For example, O_3 can cause coughing, sore or scratchy throat, inflamed airways, or difficulty breathing within hours to a day after exposure. On the other hand, SO_2 can cause breathing difficulty, wheezing, and chest tightness within 5 minutes. The variation in symptom offset is due to the specific way that the body reacts to exposure.

The AQI uses a formula to convert the averaged measurements (e.g., 24-hour average for $PM_{2.5}$, 8-hour average for O_3) to the corresponding AQI value. For real-time data, the U.S. EPA developed a method to estimate AQI from short-term averages called the NowCast AQI. The NowCast AQI shows air quality for the most current hour available by using a calculation that involves multiple hours of past data. The NowCast AQI uses longer averages during periods of stable air quality and shorter averages when air quality is changing rapidly, such as during a wildfire event. Easy-to-use online calculators are available that allow users to either calculate AQI values from measured concentrations or vice versa.

Resources for More Information

- **AirNow Air Quality Index (AQI) Website**
  - Provides information on AQI basics, air pollutants, action days, and other resources
  - https://www.airnow.gov/aqi/

- **Technical Assistance Document for Reporting of Daily Air Quality – the Air Quality Index (AQI),** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA 454/B-18-007, September 2018
  - Document provides guidance to aid local agencies in calculating and reporting the AQI as required in the Code of Federal Regulations (CFR)
  - https://www.airnow.gov/publications/air-quality-index/technical-assistance-document-for-reporting-the-daily-aqi/

- **AirNow AQI Calculator**
  - Online tool that converts user-specified AQI values into an equivalent concentration or converts concentration into AQI values. The tool also provides the corresponding AQI Category (e.g., good, moderate), health effects, and cautionary statements
  - https://www.airnow.gov/aqi/aqi-calculator/

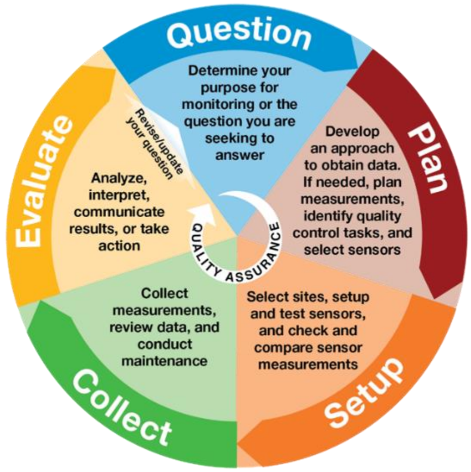
- **AirNow – Using the Air Quality Index Website**
  - Provides an overview of the AQI, AQI forecasts, and the NowCast AQI and how to use these tools to assess local air quality and plan for outdoor activities; links on the page provide technical information about NowCast algorithms and leads to a github code library for calculating the NowCast for O_3
  - https://www.airnow.gov/aqi/aqi-basics/using-air-quality-index/

- **Air Quality Index: A Guide to Air Quality and Your Health,** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-456/F-14-002, February 2014
  - Booklet that discusses the importance of air quality and provides an overview of the AQI; health effects of exposure to ozone (O_3), particulate matter (PM), carbon monoxide (CO), and sulfur dioxide (SO_2); and suggested actions to reduce exposure to unhealthy air for each AQI Category
  - https://www.airnow.gov/sites/default/files/2018-04/aqi_brochure_02_14_0.pdf

- **Air Quality Guide for Nitrogen Dioxide (NO_2),** U.S. Environmental Protection Agency, Office of Air and Radiation, EPA-456/F-11-003, February 2011
    - Booklet that overviews actions to reduce exposure NO_2 near roadways for each AQI category, provides an overview of NO_2 sources and health effects, and provides tips for reducing NO_2 emissions
    - https://www.airnow.gov/sites/default/files/2018-06/no2.pdf

- **Air Quality Guide for Ozone (O_3),** U.S. Environmental Protection Agency, Office of Air and Radiation, EPA-456/F-15-006, August 2015
    - Booklet that overviews actions to reduce exposure to O_3 for each AQI category, provides an overview of O_3 sources and health effects, and provides tips for reducing pollution from O_3
    - https://www.airnow.gov/sites/default/files/2021-03/air-quality-guide_ozone_2015.pdf

- **Air Quality Guide for Particle Pollution,** U.S. Environmental Protection Agency, Office of Air and Radiation, EPA-456/F-15-005, August 2015
    - Booklet overviews the actions to reduce exposure to particle pollution for each AQI category, provides an overview of pollution sources, and overviews health effects and tips for reducing particle pollution
    - https://www.airnow.gov/sites/default/files/2021-03/air-quality-guide_pm_2015.pdf



Chapter 3

Monitoring Using Air Sensors

Air quality monitoring, whether deploying a single air sensor or a network of sensors, requires planning. There are many steps involved in planning and conducted an air monitoring study and this chapter walks through each of those steps and will include information, considerations, and advice for each. This chapter focuses on monitoring projects which use a sensor(s) in a stationary, outdoor environment. Additional considerations may be important if you are using sensors in other applications (e.g., mobile monitoring, personal exposure, indoor air monitoring).

This chapter provides an overview of the steps involved in planning a monitoring study including:

- **Question:** determining a purpose for monitoring
- **Plan:** developing a monitoring plan including guidance for selecting a sensor to support the plan which measures the target pollutant with the general features required
- **Setup:** locating a monitoring site(s), install a sensor(s), designing a sensor network(s), and planning and conducting a collocation to determine how to interpret the sensor data
- **Collect:** reviewing data collection activities, common quality control and assurance checks, and how a data management system can support these tasks
- **Evaluate:** analyzing, interpreting, communicating, and acting on your monitoring results

3.1 Planning and Conducting Air Monitoring

Air monitoring using sensors can be complicated and requires advance planning to be successful. This planning is a critical component of **quality assurance** (QA) and is necessary to produce useful and high-quality data. The planning steps and activities outlined in this section enable users to collect quality data, build trust in the data, and allow others to use the data, as applicable.

As shown in Figure 3-1, there are five key steps in planning for air monitoring. This advance planning will save time and money and ensure that useful measurement data are collected or that the purpose of the data collection is met. The amount of time spent on each step in Figure 3-1 depends on your purpose. If deploying a single air sensor to seek knowledge for educational purposes, you can quickly consider some of the details outlined in this section to select, deploy, and operate your sensor. A more complex project requires spending time on each step and addressing the topics and recommendations presented in each section.

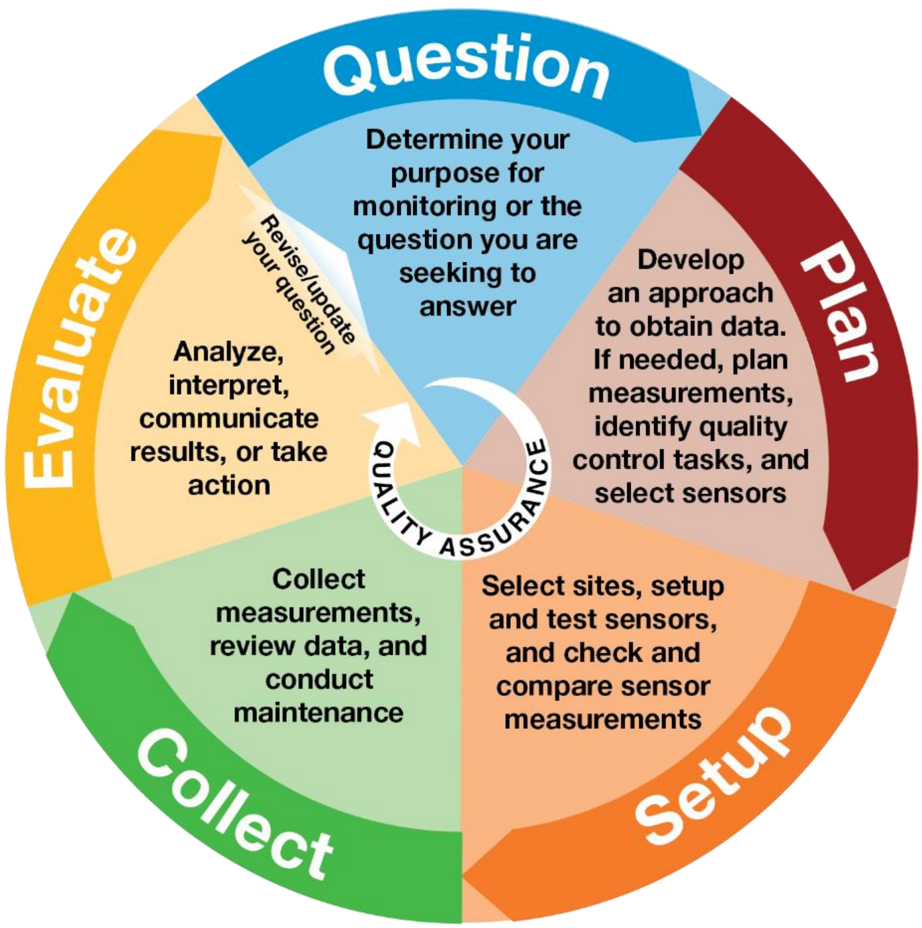


Figure 3-1. Five Steps Recommended for Planning Air Monitoring Projects Using Air Sensors

The recommended steps for monitoring include the following:

> **Do all Air Sensor Projects Need to Follow the Five Steps in the Planning Wheel (Figure 3-1)?**
>
> No. Although most sensor projects would benefit from following the five steps in the planning wheel, there are some situations where sensor data is used for educational or informational purposes only. For example, you may be interested in using a sensor to understand when the air quality is better or worse in your neighborhood. An accurate pollutant concentration may not be needed. This type of use case does not require as much planning.

1. **Question.** It is essential to take the time to establish and document the question or questions to be answered by the air monitoring study before developing a plan to collect measurements. A simple question such as, "Are ozone (O_3) concentrations in my neighborhood higher during the afternoon than in the morning?", can help you get started. See Section 3.2 for more guidance and tips on determining a monitoring purpose.

2. **Plan.** With the question posed, develop a detailed plan for how to obtain the measurements. The plan is the foundation for collecting quality data and provides a roadmap with information about staffing, sensor selection and deployment, data processing, data validation, quality control (QC) tasks, and more. See Section 3.3 for details on the components to include in a plan. Section 3.4 describes how to select an air sensor.

3. **Setup.** To ensure useful results, you should select a monitoring location(s) to measure the atmosphere or source of interest with minimal interference from the surroundings (e.g., buildings, trees). A well-placed site is key for obtaining representative data of the area being monitored. See Section 3.5 for tips on placing air sensors. Setup will often include a site where sensors can be operated side-by-side with a reference instrument, also known as collocation, to collect data useful for checking sensor operation and for developing data correction equations. See Section 3.6 for guidance on checking sensors via collocation and data correction activities.

4. **Collect.** With a measurement plan clearly defined and sensors properly located, it is time to collect data. Measuring air quality is not as easy as just turning on the sensor and collecting measurements. Periodically checking sensors throughout the course of a project is important to make sure they are functioning properly and collecting quality data. See Section 3.7 for details on collecting, managing, and quality-controlling data.

5. **Evaluate.** The approach for analyzing and presenting data is critical to successfully communicating the results and, ultimately, achieving your

objective(s) for collecting air quality data. Section 3.8 provides details about analyzing and interpreting data and communicating results.

You may find that during or after evaluating your data, some unanswered questions remain. As shown in Figure 3-1, you may need to **Revise/Update Your Question** and adjust your plan and monitoring activities accordingly. **Quality Assurance (QA)** includes all the steps you perform to plan and manage the project and to collect, assess, and review data. Completing these steps increases the likelihood of collecting credible and useful data.

3.2 Question: Determining a Purpose for Monitoring

It is essential for air sensor users to ask questions and to provide a clear monitoring goal before beginning data collection. Asking what data may already exist and why new air quality data are needed is important before purchasing an air sensor. Defining questions to be answered will help identify the pollutant of interest, the field conditions likely to be encountered, the data collection period, the type of measurements needed (e.g., short-term vs. long-term, stationary measurements), and the desired quality of these measurements. All of these data collection characteristics will determine the air sensor(s) best suited for your purpose.

As you consider your monitoring purpose, you should also consider what you will do with the information collected. Are there specific people, groups, organizations, or companies with whom you will share your findings? Are there actions that you hope to inform and inspire in yourself or others? What are some of those potential actions? These intentions may shape your question, help you recruit team members, and inform your data quality needs. Do not wait until data has been collected to determine how you will use it!

There are many purposes for monitoring with air sensors, including, but not limited to, general interest in air quality, education, and participatory science engagement; identifying an air pollutant of concern (e.g., hotspot identification); supplementing reference instruments; and conducting research. Consider the following to help identify a question that defines why monitoring air pollution might be needed:

- What is my air quality concern or suspicion?
- What do I already know about the air quality concern (being as specific as possible about when, where, and what)?
- What is not known about the situation that I want to understand?
- What do I think may have caused the situation? What are other possible causes?
- What are my desired outcomes for monitoring?
- Where are the nearest reference instruments and what pollutants do those instruments measure?
- Do the pollutants measured by nearest reference instruments reflect the sources that are of concern (see Table 2-1)?

Developing a good question is a process of a well-defined path to achieving the desired monitoring objective. Some users may start with curiosity or concern, a hunch, or suspicion about air quality, as well as ideas about the outcome(s). A good question has the following characteristics:

- It seeks to understand.
- It addresses a concern or suspicion.
- It can be answered using available resources (e.g., time, budget, skills).

You may need to modify the initial question to make it more specific and detailed as possible, as shown in Figure 3-2. Several attempts may be necessary to develop a question that has these characteristics. This upfront work helps ensure that the project achieves the desired outcome.

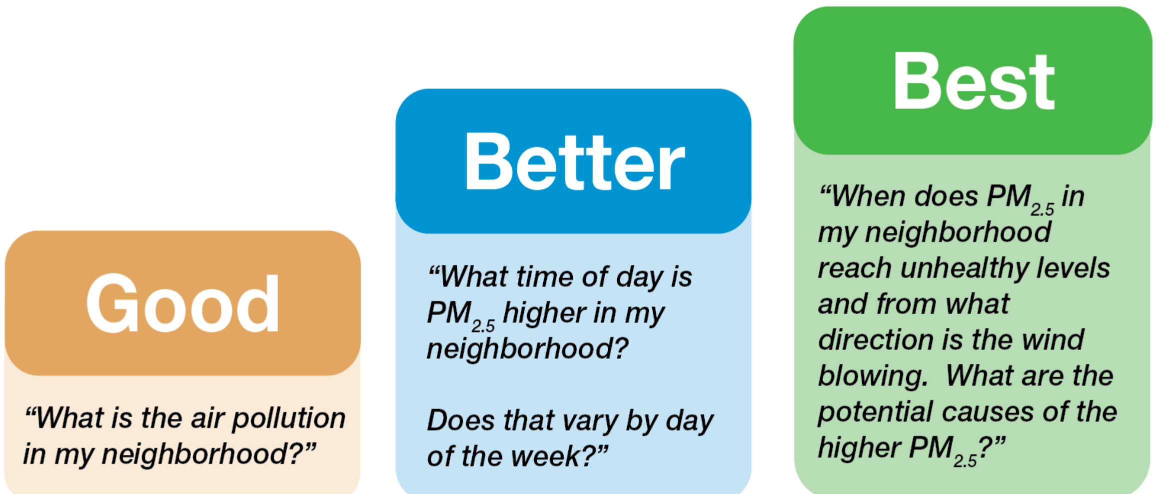


Figure 3-2. Example of Adding Details to Your Question or Objective

Resources for More Information

- **Handbook for Citizen Science Quality Assurance and Documentation**, U.S. Environmental Protection Agency, EPA 206-B-18-001, March 2019
    - Handbook that covers common expectations for quality assurance and documentation and best management practices for organizations that train and use volunteers in the collection of environmental data
    - https://www.epa.gov/sites/default/files/2019-03/documents/508_csqapphandbook_3_5_19_mmedits.pdf

- **Guidebook for Developing a Community Air Monitoring Network: Steps, Lessons, and Recommendations from the Imperial County Community Air Monitoring Project**, Tracking California, October 2018
    - Outlines the process and considerations for creating an air monitoring network using air sensors
    - https://trackingcalifornia.org/cms/file/imperial-air-project/guidebook

- **Community in Action: A Comprehensive Guidebook on Air Quality Sensors**, South Coast Air Quality Management District (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC), September 2021
    - Guidebook for community organizations that covers planning for monitoring using sensors; sensor deployment, use, and maintenance; and data handling, interpretation, and communication
    - http://www.aqmd.gov/aq-spec/special-projects/star-grant

- **Air Sensor Stories**, University of Rochester, University of North Carolina at Chapel Hill, University of Texas Medical Branch, Columbia University, and WE ACT for Environmental Justice, 2018
    - Workshop guide and supporting materials to assist diverse audiences understand the potential of air sensors in addressing community concerns about particulate matter pollution; includes an air monitoring action plan worksheet to help groups think through key questions
    - https://www.urmc.rochester.edu/environmental-health-sciences/community-engagement-core/projects-partnerships/air-sensor-stories-workshop.aspx

- **Appendix B: Questions to Consider When Planning for and Collecting Air Sensor Data, and Sharing Your Results** (*this document)*
    - Provides a list of questions for consideration to help sensor users better plan, collect, and share data

3.3 Plan: Developing a Plan

A plan should include details on the pollutant(s) and environmental parameters [e.g., temperature (T), relative humidity (RH), wind speed, wind direction] to be monitored, where the data will be collected, and how the data collection will be conducted. Whether mounting a single sensor on the side of a house to monitor air pollutants in wildfire smoke or deploying an air sensor network to assess air quality across a community (e.g., neighborhood, town, city, region) a detailed plan will help ensure that all tasks are completed and all sensors and supporting instruments (e.g., reference monitors, weather instruments) are collecting useful data for the desired application.

Creating a plan is a valuable process that can help minimize complications later. Developing a specific monitoring plan will also allow air sensor users to share the project design with others before investing time and money. Plans can vary in complexity as needed for a project and the intended use of the data. If possible, air sensor users should share their plan with an expert(s) (e.g., local air monitoring agency, university professor, environmental consultant) who is willing to provide ideas and constructive feedback. Air sensor users should also consider sharing their plan with the audience for whom the results are intended. A plan can help air sensor users identify potential problems at an early stage. Such an effort is worthwhile because it is likely that end users will need some or all of this information to answer questions about measurements when presenting results.

What is a Quality Assurance Project Plan (QAPP)?

A QAPP is a written document that explains how organizations ensure, using quality assurance (QA) and quality control (QC) activities, that the data collected can be used for its intended purpose. A QAPP gives more confidence that the data collected will meet the project objectives and help others understand the data quality.

As shown in Table 3-1, a plan can include many topics that encompass all steps for air monitoring. If you deploy a single sensor, the plan could simply guide you to consider the topics in the table. However, a detailed plan is necessary for more extensive air sensor networks, typically involving more people, organizations, and resources. In this case, the plan becomes a critical tool for success.

Table 3-1. Common Topics and Information Included in an Air Monitoring Plan

Topic	Information to Include
	Purpose and Organizational Topics
Purpose for monitoring	State the specific environmental topic/problem that is to be investigated, the decision to be made, or the outcome to be achieved using the sensor data. *(See Section 3.2)*
Project/task organization	Determine the roles and responsibilities of all key players in the project.
Engagement with local partners	Solicit insights from tribal/state/local/ air quality or health agencies, universities, research organizations, or others. Engage them early and discuss the project and desired outcomes. *(See Appendix B)*
Project/task description	Summarize the work, objectives, schedule (timeline), and expected outcomes.
Data quality objectives and criteria	Define: 1) Why data are needed? 2) Does this data already exist? 3) What measurements are needed and what do they need to represent? 4) Is there a certain level of accuracy needed? *(See Section 3.2)*
Contingency planning	Determine backup plans if something changes during the project (e.g., What happens if staff depart? How to deal with sensors that fail? What happens if my site or equipment are vandalized?). Prepare for various potential outcomes and plan troubleshooting plans.
Training and experience	Identify any training and/or certification requirements (e.g., sensor operation, programming courses through Coursera).
Documentation and records	Determine how air monitoring activities will be documented. This could include standard operating procedures (SOPs), quality assurance/quality control (QA/QC) forms, site logbooks, etc.
	Setup Topics
Measurement methods	Describe equipment and measurement methods used in the monitoring network. *(See Section 2.3)*
Siting criteria	Discuss the criteria for placing air sensors also considering site security/safety. *(See Section 3.5.1)*
Monitoring location(s)	Discuss the monitoring location or locations (for a network) selected and rationale. *(See Section 3.5)*
Instrument/equipment testing and inspection	Identify and describe how you will select the air sensor(s) and test and inspect them to determine that they are working properly. *(See Section 3.4)*
Instrument/equipment calibration and/or correction	Determine collocation locations and establish the calibration and/or collocation and data correction methods. *(See Section 3.6)*

Topic	Information to Include
Other data needed	Identify types of data that originate from other sources that may be used in the analysis. These data could include nearby reference monitor data, weather data, and/or traffic counts.
Collection Topics	
Maintenance and operations	List the methods or procedures that will be used to maintain and operate air sensors, including site visits, routine maintenance, emergency maintenance, daily data reviews, periodic collocation, etc. *(See Appendix C)*
Quality control (QC)	Describe the types of QC checks performed. *(See Section 3.7.2)*
Data processing and access	Understand how the data are processed, stored, and adjusted. Decide how you will access the data and who will own the data. *(See Section 3.7.3 and Appendix C)*
Verification and validation methods	Describe the methods or procedures that will be used to verify and validate data during the collection period. *(See Section 3.7.2)*
Data management	Determine how the air monitoring data will be managed, tracing the path of data generation in the field to the final data use and end storage. *(See Section 3.7.3 and Appendix C)*
Evaluation Topics	
Data analysis methods and visualization	Describe the methods or steps used to answer question(s) (e.g., data processing needs, visualization software needs). *(See Section 3.8)*
Compare results with original objective(s)	Describe how the results obtained from this project will be reconciled with the project's data quality objective(s). *(See Section 3.2)*
Evaluation, communication, and action	Describe how the results of the air monitoring project will be used. *(See Section 3.8)*

Resources for More Information

- **Guidance for Quality Assurance Project Plans (QA/G-5)**, U.S. Environmental Protection Agency, EPA/240/R-02/009, December 2002
    - Provides guidance on developing a Quality Assurance Project Plan (QAPP), which is an important part of the planning process for air quality monitoring projects
    - https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

- **Examples for Citizen Science Quality Assurance and Documentation,** U.S. Environmental Protection Agency, EPA 206-B-18-001, March 2019
    - Collection of examples that provide tools and procedures to help community science organizations properly document the quality of data
    - https://www.epa.gov/sites/default/files/2019-03/documents/508_csqappexamples3_5_19_mmedits.pdf

- **Templates for Citizen Science Quality Assurance and Documentation**, U.S. Environmental Protection Agency, EPA 206-B-18-001, March 2019
    - Templates that provide tools and procedures to help properly document the quality of data
    - https://www.epa.gov/sites/default/files/2019-03/documents/508_csqapptemplates3_5_19_mmedits.pdf
    - *Editable templates*: https://www.epa.gov/citizen-science/quality-assurance-handbook-and-guidance-documents-citizen-science-projects

- **Community Science Air Monitoring**
    - Guidance, provided by the New Jersey Department of Environmental Protection Division of Air Quality – Air Monitoring, on using air sensors for community projects; includes approaches to using sensors, types of sensors available, interpreting sensor data, four types of sensor projects and data quality assurance plan templates for each, and other helpful links
    - https://www.nj.gov/dep/airmon/community-science.html

- **Air Quality Agencies**
    - Websites that provide a list of state, local, and/or tribal agencies that manage air quality
    - *U.S. Environmental Protection Agency*: https://www.epa.gov/aboutepa/health-and-environmental-agencies-us-states-and-territories
    - *National Tribal Air Association (NTAA)*: https://www.ntaatribalair.org/
    - *National Association of Clean Air Agencies (NACAA)*: https://www.4cleanair.org/agencies/
    - *Association of Air Pollution Control Agencies (AAPCA)*: https://cleanairact.org/about/

3.4 Plan: Selecting an Air Sensor

Before purchasing an air sensor, evaluating specific criteria will help you match air sensors to your application of interest and purpose for collecting data. Figure 3-3 provides an overview of six important questions to ask before purchasing an air sensor. The key sensor selection criteria are discussed in additional detail below.

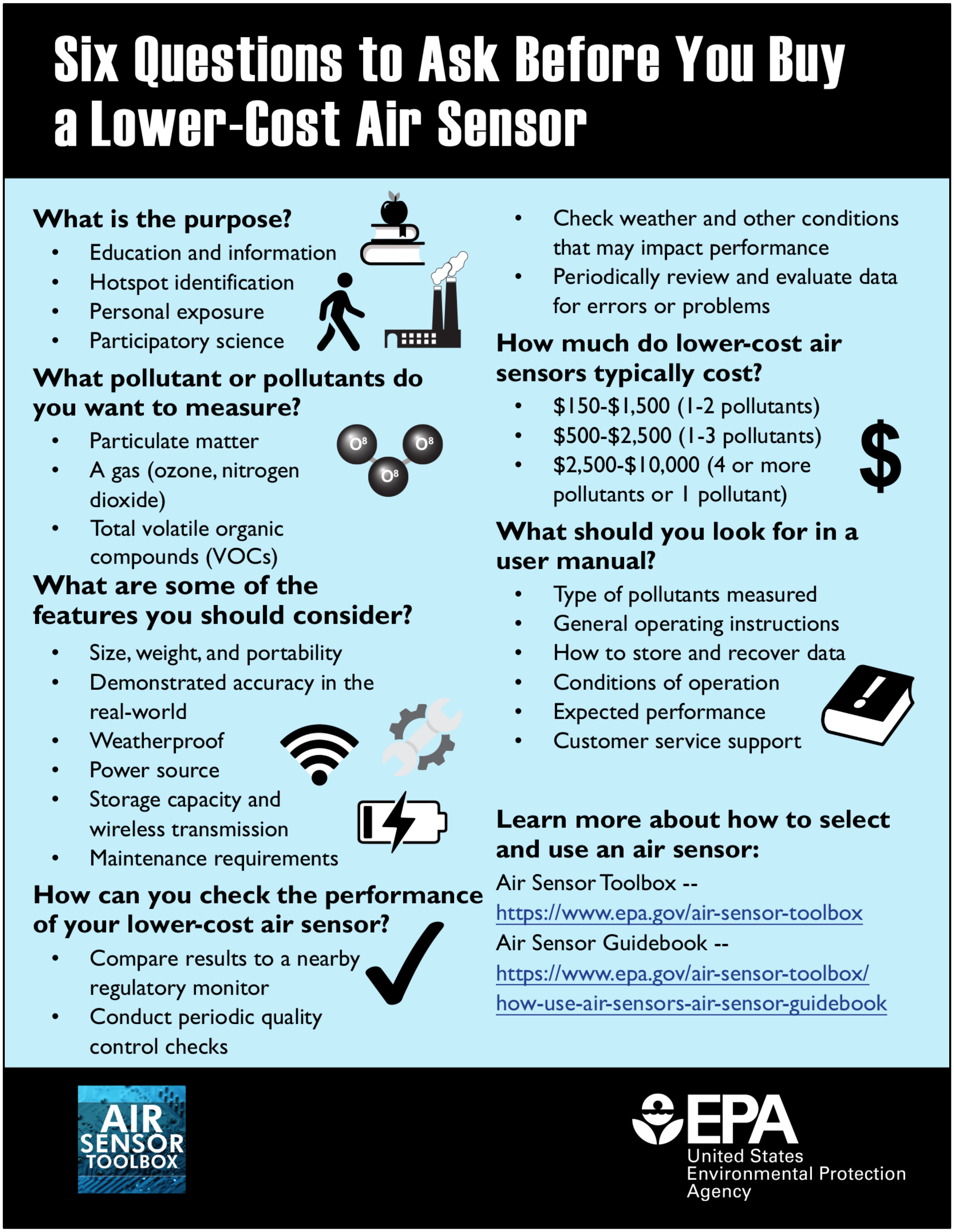


Figure 3-3. Questions to Consider Before Purchasing an Air Sensor

3.4.1 Target Pollutant and Sensor Performance

Selecting a target pollutant. The target pollutant(s) to be measured by the sensor will depend on the question asked and the purpose for monitoring. Consult Tables 2-1 and 2-2, which identify common sources and health effects of various pollutants. It is important to keep in mind that a sensor's cost may depend on the types and number of pollutants selected. For each target pollutant, consider the other factors below (e.g., detection limit, measurement range, accuracy) to determine if a sensor will meet your monitoring needs.

How Do Air Sensors Work?

Sensor design and performance is an active area of research and innovation. New methods may be introduced over time.

PM (PM_{10}, $PM_{2.5}$) sensors: Currently, PM is typically measured using an optical approach where light scattered by a particle(s) is used to estimate the particle mass concentration. The amount of light scattered can vary due to the size, shape, and chemical composition of the particles. This method can only detect a narrow range of particle sizes. Over time, particles may build up within the sensor causing changes in performance. Lifetimes vary but are often between 1 to 4 years. PM sensors are typically useful for outdoor, indoor, and smoke monitoring applications. Currently, many sensors will not detect PM_{10} or dust.

Gas (O_3, NO_2, CO, SO_2) sensors: Currently, most gas pollutants are measured using either electrochemical (EC) or metal oxide sensors (MOSs). They may respond to the target pollutant, changes in T or RH, or other interferent gases. Sensors may lose sensitivity over time whether in use or not and should be collocated at least seasonally. Lifetimes may be between 6 months and 2 years. Measurements at low concentrations are often difficult and the most successful application for some sensors may be near sources.

Total VOC (tVOC) sensors: Currently, most tVOC sensors are MOS or photoionization detector (PID) sensors. They detect a wide variety of VOCs but do not measure all VOCs and are more responsive to some compounds than others. Therefore, the reported concentration cannot be attributed to a specific compound or even the sum of several compounds. Sensors may also respond to changes in T, RH, other interferent gases. Currently, the most successful applications match upwind and downwind measurements near a source to look for spikes which may indicate a VOC emission event. Lifetimes may be months to a year for PID sensors and longer for MOS.

Measurement range and detection limit. Air pollutants can often be present at very low or very high concentrations in the ambient air. The *measurement range* refers to the lowest and highest pollutant concentrations that a device can measure. A sensor will be most useful when it measures a target pollutant over the full range of concentrations commonly found in the atmosphere (consult Table 2-1 under “Range to Expect” for each pollutant). Depending on proximity to a pollution source, the sensor’s ability to measure either very low or very high concentrations is essential. The *detection limit* is the lowest concentration of a pollutant that a device can routinely detect. It is important to consult the manufacturer's specifications for the detection limit to ensure that the air sensor can measure lower concentrations that are typically found within the U.S.

Sensor accuracy. *Accuracy* describes the agreement between the sensor's pollutant concentration measurement and the concentration measured by the reference instrument. The accuracy of a sensor is determined by two components: precision and bias. *Precision* refers to how well a set of sensors reproduces the measurement of a pollutant under identical conditions (e.g., same concentration and temperature). *Bias* refers to measurement error. For example, a sensor may always measure a little higher or lower than the true concentration. Figure 3-4 shows example plots illustrating accuracy, precision, and bias. Before purchasing a sensor, buyers should evaluate the air sensor's precision and bias using the manufacturer's specifications, evaluation reports, and published literature (further discussion in Chapter 4). Also, users should conduct checks of the precision and bias to qualify the air sensor's accuracy. See Sections 3.6.1, 3.6.2, and Chapter 4, which describe how to perform these checks through collocation.

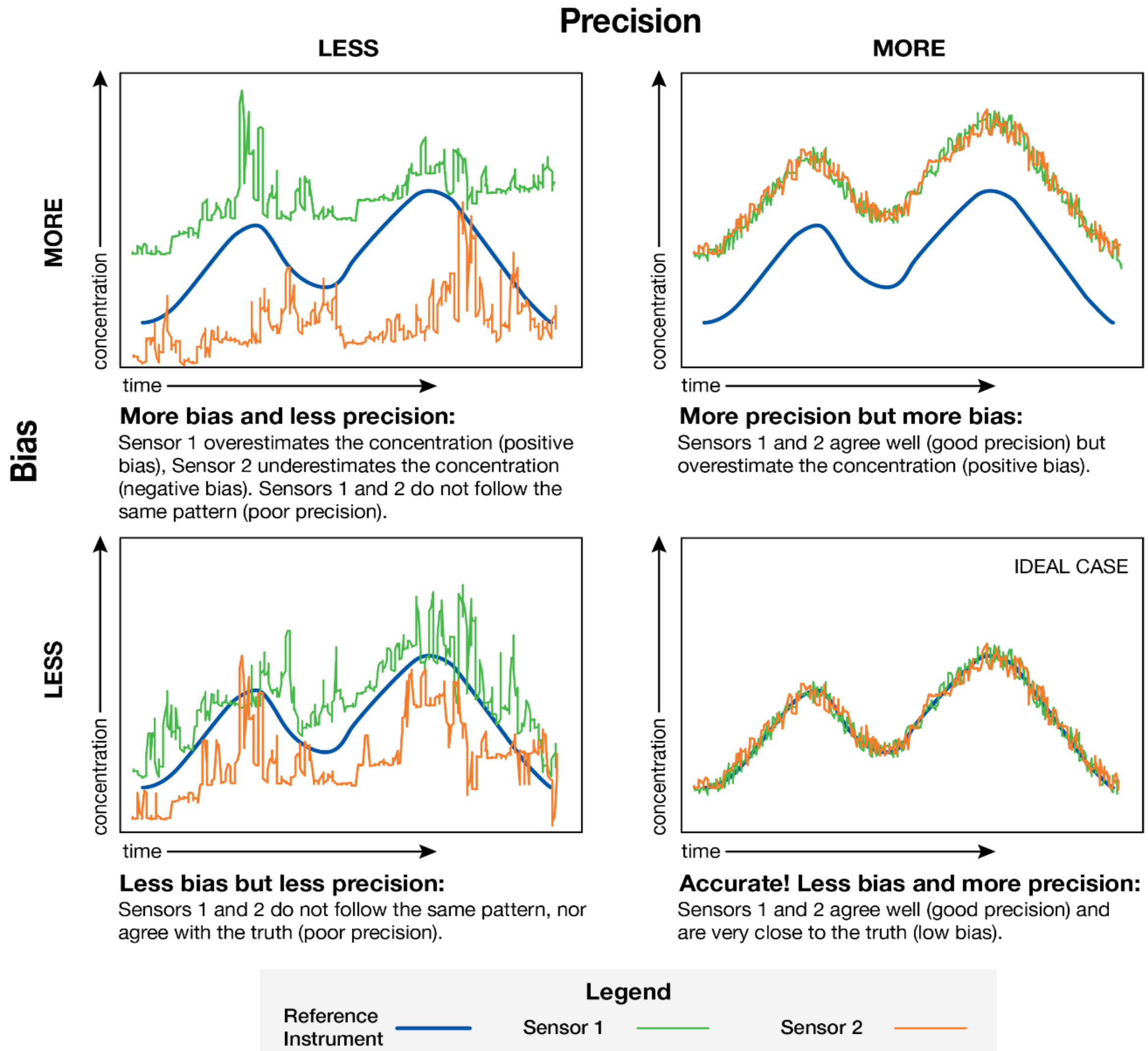


Figure 3-4. Illustration of Air Sensor Bias, Accuracy, and Precision

Users should be aware that a sensor's accuracy, precision, and bias can change over time. For example, exposure to warm temperatures or humid air may lead to a gradual increase in sensor bias. Ozone (O_3) sensors, in particular, can become less sensitive over time either because of age or fluctuations in temperature and humidity. Particulate matter (PM) sensor bias may change if pollutant source, particle type, or particle size changes. The sensor may also experience interference from other pollutants in the atmosphere, leading to inaccurate concentration measurements (see Section 3.7.2). Some sensor manufacturers provide an expiration date, after which the sensor measurements are no longer likely to be accurate.

Air sensor data are called "noisy" when the data fluctuates from one value to another. *Noise* in the data can be caused by multiple factors including electrical interferences, sensor precision, rapid weather changes, and averaging period. To reduce the noise, air sensor data are often averaged over longer time periods to make it easier to see trends in the data. For example, 1-minute $PM_{2.5}$ data can oscillate rapidly from one minute to the next. Averaging 60 of these 1- minute data points to create a 1-hour average will reduce the noise in the data. Figure 3-5 shows an example of noisy versus less noisy data.

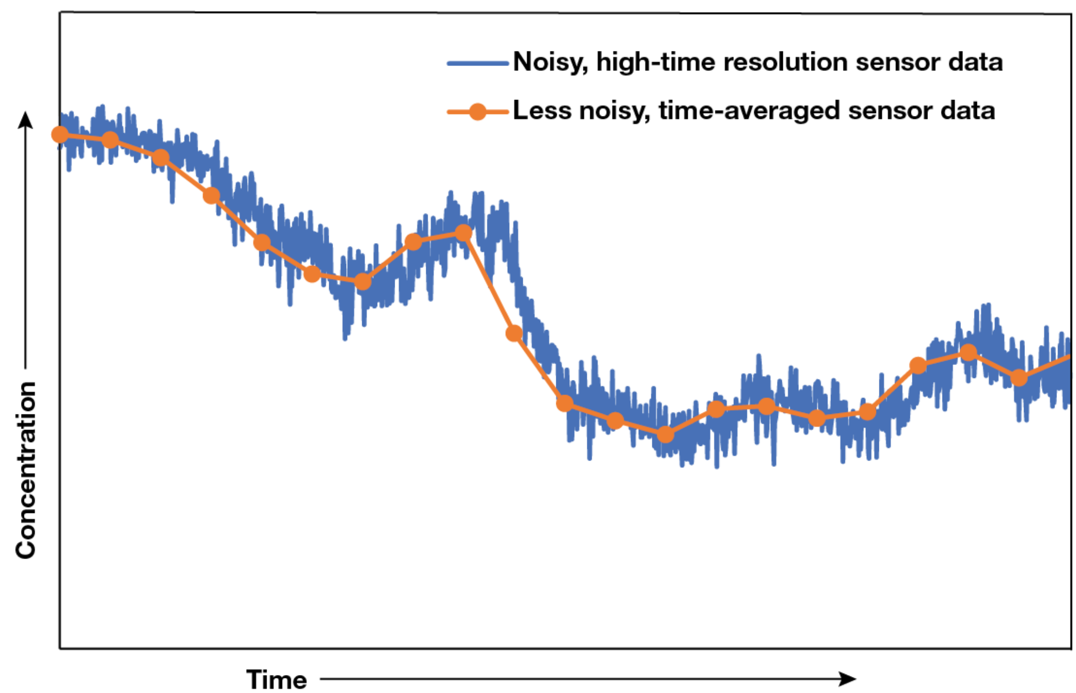


Figure 3-5. Example of Noisy Measurement Data

Calibration or collocation and data correction. *Calibration* is a procedure that checks and adjusts an instrument's settings so that the measurements produced are comparable to a certified standard. *Collocation* is the process of checking the performance of an air sensor by installing and operating a sensor in close proximity to a reference instrument(s). Data *correction* involves adjusting the air sensor data to increase its accuracy relative to a known reference value. Section 3.6 provides guidance on calibration, collocation, and correction. Before purchasing a sensor, users should determine whether the manufacturer has calibrated or corrected the sensor. In addition, users should fully understand when and how collocation should be performed and how to correct the air sensor's measurements. Talk to the sensor manufacturer about the method, frequency, and any additional costs for the calibration or collocation and correction services.

Response time. A sensor may be quick or slow to detect changing pollutant concentrations in the air. A sensor that responds quickly (i.e., high time resolution) may be useful for mobile monitoring and observing very rapid (e.g., seconds to minutes) changes in pollutant concentrations at fixed sites (such as near roadways with heavy traffic), as shown in Figure 3-6. A sensor that responds slowly (i.e., low time resolution) may be more suited to stationary monitoring where pollutant concentrations often change more gradually (e.g., minutes to hours). Specific data collection goals and purposes will determine which type of sensor is best.

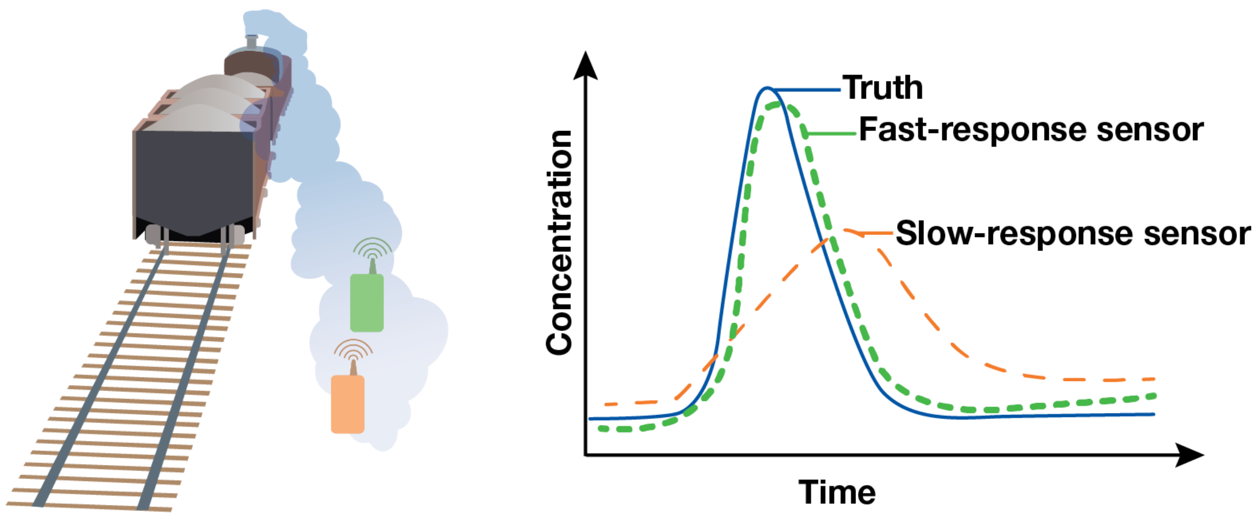


Figure 3-6. Example of an Air Sensor's Response Time

3.4.2 General Features of a Sensor

Durability. Sensors vary in size, shape, durability, and quality of construction. *Durability* refers to an air sensor's ability to be shipped, moved, and to endure wear and tear and continue to perform. For example, sensors are often tossed around during shipping and some components or parts could dislodge inside causing anything from communication or data logging issues to complete destruction. Sensors that are worn by the user or are deployed for mobile monitoring on vehicles might be shaken, hit against other objects, or dropped and must be designed to handle these impacts. All sensors measuring outdoor air quality are likely to be exposed to variable weather conditions such as wind, heat, cold, moisture, and dust and should be built to handle this exposure. A user manual or manufacturer's specification sheet should provide details on the general durability of the sensor.

Enclosure. An *enclosure* is a case or structure that contains the sensor and its components and protects the components from water, light, temperature variations (e.g., by adding heaters or cooling fans), and electromagnetic noise. The sensor enclosure must allow air to reach the sensing components while shielding the components from weather effects. The materials, design of the enclosure, and sensor orientation (e.g., air inlet location, air flow path) may affect measured pollutant concentration levels and response time. For example, certain types of plastics and coatings might react with the pollutant of interest or release the pollutant, interfering with the air sensor’s measurements. In addition, the enclosure may impact the internal T or RH, potentially also impacting the air sensor's measurements. Sensors that are exposed to ambient conditions for an extended period of time may experience a build-up of dust, dirt, ice/snow, and other debris near the sensor inlet. This may alter the accuracy and bias of the sensor, and users should ensure that a sensor’s inlet remains clear of obstruction.

Ease-of-use. A wide variety of people with different levels of experience may use an air sensor and it is important to understand how easy or difficult it is to operate a sensor. Everyone, especially less experienced users, appreciate sensors that are easier to use. Determine whether any special expertise (e.g., technician, programmer) or tools (e.g., ladders, computers with specific software, special screwdrivers) are needed to operate or maintain the sensor both in the short term and long term.

Power. Power requirements vary for sensors and include plug-in, battery, or solar power. The choice of power options will depend on a user’s application. Some sensors may alter their sampling frequency depending on the type of power supply used. This may result in some sensors logging data at intervals spaced longer apart when configured for battery or solar-powered operation. Plug-in devices are best suited for stationary monitoring applications with access to a wall power outlet; however, users need to ensure that power is available and easily accessible at the installation site. Battery-powered devices are often suitable for mobile applications or short-term data collection activities, although users should be aware of how long the battery lasts after charging and at what point the charge is too low to fully operate the sensor. For solar-powered devices, users should consult the manufacturer to ensure proper sizing of the solar components for the device and the available sunlight at the monitoring location (e.g., latitude, longitude, season) and information about proper placement, orientation, and maintenance. If you need to design your own solar option, some commercial solar kits may be available which contain solar panels and batteries. Consult the supplier to learn more about proper sizing, including a margin of error for hours without adequate sunlight (e.g., cloudy or smoky days, overnight). Keep in mind that a solar power solution can be costly.

Display. Some sensors do not include a data display and require users to visit a website or use an app to view data instead. Others feature a screen or display allowing users to view sensor information, real-time data, and/or view historical data. Some sensors include lights which indicate power or may change color depending on pollutant concentration and these lights may be paired with a data screen or be the only form of display. Consider whether a display is necessary for your project.

Data transmission. There are several options available for data transmission. Options vary from sensor to sensor and include, but are not limited to, cellular, WiFi, Bluetooth, satellite, and low-power wide-area network (LoRa). Some sensors store data on the unit itself (e.g., local on-board storage, memory card) and data must be transferred manually. When selecting sensors, users should consider their application and whether the sensor's data transmission methods will suit their needs, cost constraints (e.g., subscription costs associated with cellular services), and will work in their desired monitoring location.

Data access. There are a variety of data storage options available that may influence data access options. Sensors with on-board data storage require physical data download. Other sensors communicate data to central servers and data can be accessed by remote download or call from an Application Programming Interface (API). Users should consider how the data can be accessed, who has permission to access, who has data ownership rights, and how long the data will be available. Once data can be accessed, users will need to fully understand the data format, data analysis, and visualization options. For devices that share information with the public, carefully consider what information is shown as there may be privacy concerns (e.g., sharing a specific address).

Data handling. Conversion of information from the raw sensor signal to the final reported pollutant concentration happens in a variety of ways but often involves some kind of mathematical equation or model. These methods may depend only on data collected on-board the sensor or may include other data (e.g., nearby weather station). Users should ask manufacturers to describe how data is processed and any of these other data dependencies to understand whether that data will be available in their study area. Sensor manufacturers may choose to make their data handling methods public or keep them proprietary.

Cost. A sensor's cost may vary greatly depending on the pollutant measured and degree of accuracy and sensitivity needed. Even for sensors measuring the same pollutant, the costs can vary depending on the device's features. Some sensor manufacturers offer different purchasing options, including buy, lease, or rent. Users should be aware that there are upfront costs (e.g., purchasing the sensor and sensor components) and long-term costs that can include, but are not limited to, repair or replacement of the sensor and their components, calibration services, data transmission charges (e.g., cellular service), or data hosting and storage fees (e.g., cloud storage on a manufacturer server or other server). Additionally, other potential costs (or time) could include data analysis, interpretation, and communication of air sensor data. Of course, costs increase if more sensors are needed (e.g., sensor networks).

Resources for More Information

- **Chapter 4: Sensor Performance Guidance *(this document)***
  - Provides an overview of laboratory and field sensor performance evaluations; performance characteristics needed for spatiotemporal variability, comparison, and long-term trend NSIM applications; and U.S. EPA's recommendations for sensor testing protocols, performance metrics, and targets

- **Appendix C: Choosing Air Sensors *(this document)***
  - Provides checklists for: (1) what to look for in a sensor before buying, (2) what to look for in a sensor user manual, and (3) sensor maintenance to ensure proper functionality and reliable performance

- **Performance Testing Protocols, Metrics, and Target Values for Ozone Air Sensors – Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications**, U.S. Environmental Protection Agency, EPA/600/R-20/279. February 2021
  - Provides recommended testing protocols (field and laboratory), performance metrics (parameters used to describe sensor data quality), and target levels to evaluate ozone air sensors
  - https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=350784&Lab=CEMM

- **U.S. EPA's Performance Targets and Testing Protocols Website**
  - Summary of the U.S. EPA's research on recommended testing protocols, metrics, and target values for evaluating the performance of air sensors
  - https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

- **Air Quality Sensor Performance Evaluation Center (AQ-SPEC) of the South Coast Air Quality Management District (South Coast AQMD) Website**
  - Website for the AQ-SPEC program which conducts laboratory and field evaluations of air sensors and provides information to the public regarding actual sensor performance and the advantages and potential limitations of using air sensors. AQ-SPEC is operated by South Coast AQMD
  - http://www.aqmd.gov/aq-spec

- **The National Solar Radiation Data Base (NSRDB)**, Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby. *Renewable and Sustainable Energy Reviews* 89 (2018): 51-60
  - Paper reviews the complete package of surface observations, models, and satellite data used for the NSRDB – an open dataset of solar radiation and meteorological data over the United States and regions of the surrounding countries
  - https://www.sciencedirect.com/science/article/pii/S136403211830087X

3.5 Setup: Locating Sites for Air Sensors

Finding locations to set up air sensors, whether a single air sensor or a network of sensors (and other instruments), is a critical task. Finding suitable sites enables air sensors to collect useful data representing the surrounding conditions, ensures the sensor has power (and internet access, if needed), provides security for the sensor, allows easy access for maintenance, and adds credibility to the data.

Section 3.5.1 provides recommendations for placing an air sensor at a specific site. Section 3.5.2 provides information on designing a network of air sensors (i.e., multiple air sensors placed at different locations). This entire process, including evaluating logistics like site access and security, can be time consuming so users should start early to find suitable locations.

Tip: Start the process of locating sites for air sensors as early as possible

Locating sites for air sensors is time consuming with lots of logistics. It is best to start early to find good locations. A simple flyer about the project and sensor details (e.g., power, size, weight, access needs) may help you communicate with owners of potential sites at homes and businesses.

What is an Example of How you Would Select Monitoring Locations Based on Your Purpose for Monitoring?

Let's say your study **question** is "What are the typical particulate matter concentrations in my city? Where are concentrations highest?"

Here are some potential **monitoring locations** based on the study **question:**

- Where people live/work
- Near locations where many people gather
- Near susceptible and sensitive populations (e.g., schools, hospitals)
- Between gaps in an existing regulatory monitoring network
- A background site (e.g., an area not impacted by the suspected pollution source)
- Near the actual (or expected) maximum concentration
- At or near emissions source(s) of concern
- Upwind/downwind of emissions source(s)
- Next to a site with reference monitors for collocation/correction activities

3.5.1 Installing Air Sensors

Users should carefully place a sensor or instrument in a location where it can reliably and safely measure the ambient air or source of interest with minimal interference from the location's surroundings. A well-placed sensor yields data that are representative of the air quality in the area being monitored.

Air pollution concentrations can be affected considerably by local sources (e.g., fire pit, grill), buildings, and structures, among other factors. These factors may vary based on the target pollutant or monitoring goal and users should consider the potential effects of these factors when choosing a monitoring location. The data will be most useful if the sensor can measure the pollutant of interest with little impact from other sources at the site. Figure 3-7 provides eight key considerations when placing an air sensor at a specific location.

Figure 3-7. Logistical Considerations and Tips for Installing an Air Sensor

Location. Before setting up a sensor, it is useful to consider your monitoring goals since they can impact your ideal location selection. For example, a sensor that will be used to monitor for emissions from idling buses may be setup in a different location than one used to estimate the local ambient air quality index (AQI).

Access. Although easy to use, air sensors are generally not something you can "set up and forget." You will want to access your site to install and periodically check on the sensor. If you do not control the site, you will want to determine permissions, access requirements, and any limitations on access frequency or timing during the planning stage. Some users have found formal access agreements helpful in explicitly defining these conditions.

Power. Air sensors may need to be plugged in, may have solar panels, or may offer both options. Some sensors that offer power options may operate differently depending on which option is used (e.g., the data reporting frequency may change). Be sure to consult the sensor manufacturer to understand the implications. It can be expensive and time consuming to deliver power to a location that does not have the existing infrastructure. Available outlets should be tested rather than assuming they work. Consider using a surge protected power strip so that others can also use the outlet without unplugging your sensor. Extension cords may be needed for optimal sensor placement safety (e.g., trip hazard, fire risk). Water and electricity don't mix so be sure to consider electrical safety and water proofing for all connections. Solar panels may not be adequate if your location does not get enough sun and they will need periodic maintenance to remove dust. Areas that experience public safety power shutoffs may benefit from solar power to prevent monitoring interruptions.

Communications. Sensors may communicate data to a cloud-based interface using a variety of technologies (e.g., cellular, WiFi, LoRa). Some sensors may offer just one option, while other sensors may provide multiple options. Be sure to consult the manufacturer to understand specific requirements such as network limitations (e.g., 2G, 5G), carrier limitations (e.g., Verizon, AT&T), area coverage (U.S. and international), and signal strength needs. If supplying your own mobile hotspot, you may also want to know the typical data use to properly estimate costs and if the sensor settings can be adjusted to reduce data use.

Tip: Also consider time-based factors when locating monitoring sites

Sensors are commonly used to monitor air quality before and after implementation of emission reduction programs (e.g., anti-idling campaigns), changes in land use, and changes in industry. Don't forget that collecting measurements before AND after will be useful to understand air quality impacts. Also consider collecting measurements during different seasons (e.g., summer vs. winter).

Security. Sensors and their peripheral equipment (such as solar panels) are subject to tampering and theft. A small sign describing your project and the device may help. Users will want to consider placing sensors in secure locations. Ideas include mounting a sensor overhead out of arms reach, in an inconspicuous location, or behind a locked gate or fence. When considering secure locations, keep in mind that sensors need a free flow of air, and consider your physical safety when visiting the area or even while climbing a ladder or stepstool for installation or maintenance.

Placement. It is ideal to place sensors near the typical breathing zone height (3-6 feet). Sensors should be placed away from pollutant sources (e.g., fire pit, grill) or pollution sinks (e.g., trees, shrub barrier) to get a more representative measure of air quality within the local area. Sensors should also be located to allow for free air flow to the sensor. Avoid placing sensors near high voltage power lines, which may create electronic interferences. Consider what hardware might be needed to mount the sensor (e.g., tripods, poles). Note that some locations (e.g., on top of buildings) may have specific engineering requirements to withstand wind, etc.

Photos. Photos of the sensor deployment may assist you with data interpretation later. Be sure to photograph nearby features that may impact the sensor readings. Outdoors, this may be nearby buildings, roadways, or landscapes. Indoors, this may be building features like windows, doors, and exhaust vents. The photos should also capture the typical use of an area or room where the sensors are placed. Make sure to have written or verbal consent when taking photos of anyone in the community, especially children.

Additional Documentation. A deployment log can assist you in recording notes about sensor placement (e.g., location, height, date of installation) and maintenance (e.g., cleaning, component replacement). It's easiest to track or tag this information by assigning each sensor an ID (e.g., serial number, user given name). You may also want to capture more information about how the area is used. Also consider that temporary activities (e.g., road work, construction activities, cleaning, cooking) may impact the area and confuse data interpretation, so keep notes while the sensor is in use.

3.5.2 Specifics for Designing a Network of Air Sensors

An **air sensor network** is made up of two or more sensors placed at several different locations in an area to gain more information about variations in pollutant concentrations. Examples of a network include deploying air sensors throughout a neighborhood to gather general knowledge of air pollution levels or, designing a monitoring network to locate the potential source of pollution impacting a location.

Selecting general locations for an air sensor network may seem daunting at first. This section outlines considerations to help users design a successful and purposeful sensor network.

Start by answering some questions about why and where to collect measurements, such as:

- What types of changes in air quality do I expect in the area?
- How do I expect one site to be different than another?
- Where should I put sensors to measure and show these differences?
- What is the typical or prevailing wind flow in the area and how might winds transport pollutants?
- Do I need meteorological data to interpret the air quality data?
- Could I use data from existing air monitoring networks?
- What is my budget for air sensors and approximately how many can I afford? (Some air sensors may fail, so plan for extras or replacements.)

Identify the general locations on a map to place air sensors. Consider the following tips:

- Spread out the deployment locations to get good spatial coverage.
- Avoid hyperlocal sources (e.g., smoking stations, grills) and locations where winds can channel and trap pollutants unless that is your specific research question.
- If there is an area of concern (e.g., pollutant source, area of suspected higher concentrations), locate sensors near/inside the area of concern AND upwind and downwind of the area (see *Section 2.1* and Figure 3-8) so that meaningful comparisons can be made.
- Account for factors that affect safety when installing and maintaining the sensors that include access to facility, security, signage, weather conditions (e.g., lightning), etc.
- Locate a reference instrument for future collocation activities (see *Section 3.6*).

Seek input from your local air quality agency, a university professor, environmental consultant, or other experts who are useful resources to help design effective sensor networks.

- Contact your tribal, state, or local air quality agency.
- Contact professors in academic institutions with expertise in air quality such as environmental studies, engineering, atmospheric science, or other sciences.

Air sensor networks may have different scales depending on the purpose for collecting measurements. Figure 3-8 shows examples of air sensor networks of different scales for three examples.

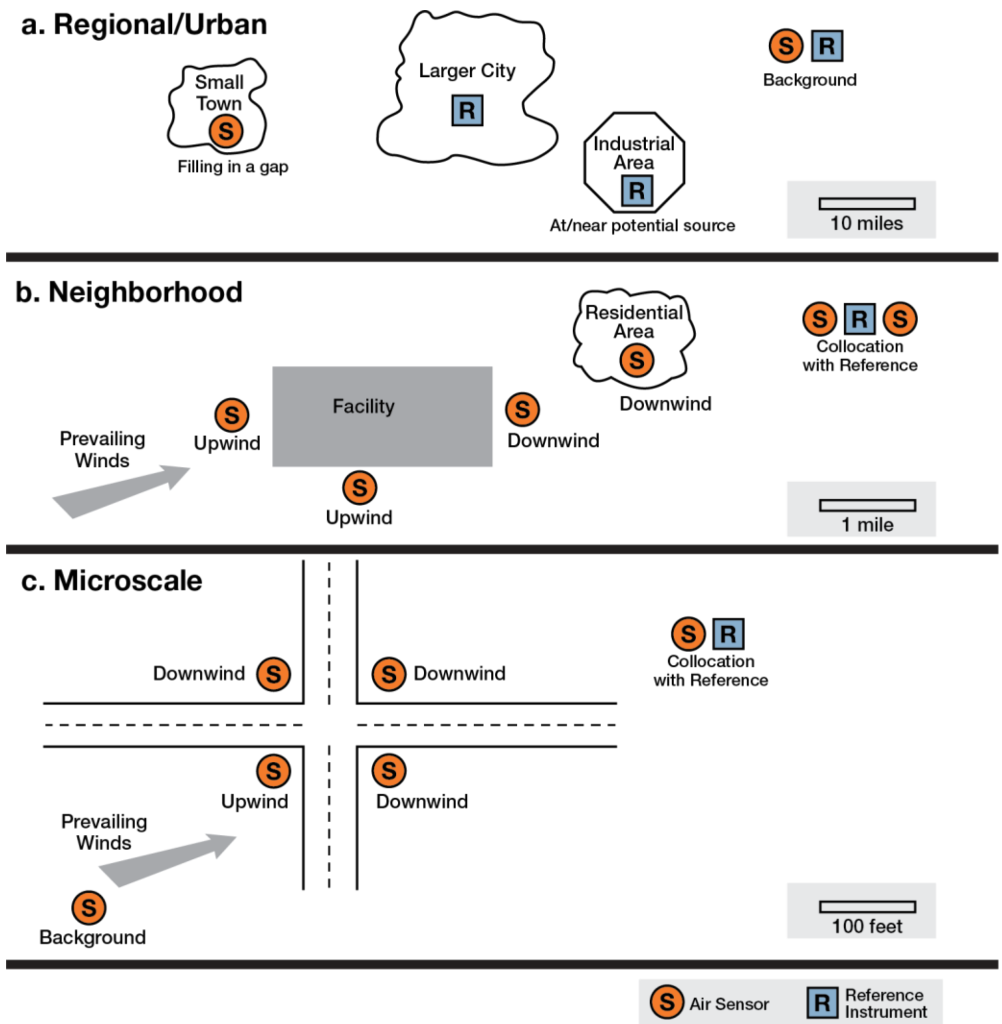


Figure 3-8. Example Maps for Placing Air Sensors for Networks of Different Scales Depending on the Purpose: a) Regional/Urban Network, b) Neighborhood Network, and c) Microscale, Small Area Network

In each panel, Figure 3-8 identifies an optimal sensor collocation site. Generally, collocation is recommended for any monitoring activity to make sure the air sensor is reporting accurate data (see *Section 3.6.1* for more information). The examples for the different scales of sensor networks and potential collocation approaches are described below.

Figure 3-8a shows an example of using an air sensor to fill in an air monitoring gap. This regional and urban network consisting of reference instruments located in a larger city, an industrial area, and a background site. Air sensors can fill in the gap in this network by providing air quality information for a small town that does not have existing reference monitors. In this case, the air quality at the background site is most similar to that of the small town experiencing similar meteorological conditions (e.g., T, RH), pollutants, and pollutant concentrations. The pollution sources would be different, and the pollutant concentrations would likely be higher, at the other two reference sites. Thus, in this example the collocation is conducted at the background site collocating a sensor with the reference instrument at that location.

Figure 3-8b shows an example sensor network for a neighborhood or residential area concerned about pollutant emissions from a nearby facility. The network measures air quality around the facility (both upwind and downwind) and in the residential area located downwind. The network also includes two air sensors collocated next to a reference instrument. The collocation provides data to assess the accuracy of the sensors and develop corrections for the other sensors in the network (see *Section 3.6* for more details about collocation and correction). The two collocated sensors provide replicate measurements which allows for some additional quality assurance because the measurements can be compared.

In Figure 3-8b, users can potentially determine the impact on air quality due to the facility of concern by comparing the upwind and downwind pollutant concentrations. For this type of example network, knowledge of the prevailing wind direction is critical and users will likely need to place air sensors at several locations to make upwind and downwind measurements under a variety of wind conditions. Locations upwind of the facility represent the background air quality conditions before the air flows over the area of concern. The locations downwind of the facility represent the air quality after winds pick up pollutant contributions from the facility. In this case, wind speed and wind direction measurements would be helpful for data interpretation.

Figure 3-8c shows an example of a microscale (small area) network using air sensor measurements to assess the contributions to air pollution due to vehicle traffic at an intersection. A background sensor measures the general air quality in the area outside of the intersection of concern. An upwind air sensor measures the air quality before the air flows through the intersection, and downwind air sensors measure the air quality after the intersection. Comparing the upwind and downwind concentrations allows users to evaluate the traffic's contribution to air quality. As with the neighborhood network in Figure 3-8b, users will need to consider the direction of prevailing winds to determine appropriate background, upwind, and downwind sensor locations. In this case, sensors can be collocated at a nearby reference site which experiences similar pollutant concentrations and meteorological conditions and is also impacted by nearby traffic sources.

For networks where the objective is to compare sensor measurements collected at different sites, it is critical to first evaluate the **precision**, or agreement of the measurements made by all the sensors. This can be accomplished by **collocating** all air sensors to evaluate the precision and bias of each air sensor's data and then using that relationship (e.g., equation) to apply **correction(s)** to all the sensors used in the network so that the data from all of the sensor are more comparable (see *Section 3.6.2* for more information including additional considerations and tips). By taking this one step further and collocating the air sensors with a reference instrument, a correction equation can be developed to make the sensor data more comparable with the reference data thereby allowing comparisons to be made among both the sensor and reference instruments.

In summary, a wide range of networks can be designed to provide general air quality information in an area, collect data for specific research questions, and more. Collocation is highly recommended to make sure the air sensor(s) is reporting accurate data.

Resources for More Information

- **U.S. Code of Federal Regulations (CFR), Title 40 (Protection of Environment), Chapter 1 (Environmental Protection Agency), Subchapter C (Air Programs), Part 58 (Ambient Air Quality Surveillance)**
  - Specifies the regulatory requirements for the U.S. ambient air quality monitoring network including quality assurance procedures for operating air quality monitors and handling data; methodology and operating schedules for monitoring instruments; criteria for siting monitoring instruments; and air quality data reporting requirements
  - https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-58#ap40.6.58.0000_0nbspnbspnbsp.e

- **Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II**, Ambient Air Quality Monitoring Program, U.S. Environmental Protection Agency, EPA-454/B-17-001, January 2017
  - Handbook provides additional information and guidance (including pollutant-specific spatial scale characteristics) to assist tribal, state, and local monitoring organizations in developing and implementing a quality management system for the Ambient Air Quality Surveillance Program described in 40 CFR Part 58
  - https://www.epa.gov/sites/default/files/2020-10/documents/final_handbook_document_1_17.pdf

- **Air Quality Agencies**
  - Websites provide a list of state, local, and/or tribal agencies that manage air quality
  - U.S. Environmental Protection Agency: https://www.epa.gov/aboutepa/health-and-environmental-agencies-us-states-and-territories
  - National Tribal Air Association (NTAA): https://www.ntaatribalair.org/
  - National Association of Clean Air Agencies (NACAA): https://www.4cleanair.org/agencies/
  - Association of Air Pollution Control Agencies (AAPCA): https://cleanairact.org/about/

- **Blueprint for the Development and Implementation of Distributed Sensor Networks**, U.S. National Institute of Standards and Technology Global Cities Team Challenge Transportation SuperCluster

- Blueprint that summarizes lessons learned, best practices, and research questions for developing and implementing sensor networks
- https://static1.squarespace.com/static/5967c18bff7c50a0244ff42c/t/5ad7c41c758d464041c7e58a/1524089886422/Distributed_Sensor_Networks_Recommendations.pdf

- **U.S. EPA Guide to Siting and Installing Air Sensors**
  - Information and considerations for locating an air sensor in both outdoor and indoor locations
  - https://www.epa.gov/air-sensor-toolbox/guide-siting-and-installing-air-sensors

- **South Coast Air Quality Management District - Sensor Siting and Installation Guide**
  - *Guidance on how to locate and install air sensors:* http://www.aqmd.gov/aq-spec/resources/related-documents
  - *English:* http://www.aqmd.gov/docs/default-source/aq-spec/resources-page/aq-spec-sensor-siting-and-installation-guide_v1-0-(english).pdf
  - *Spanish:* http://www.aqmd.gov/docs/default-source/aq-spec/resources-page/sensor-siting-and-installation-guide_v1-0-(spanish).pdf

- **U.S. EPA Air Sensor Toolbox – Air Sensor Research Grants and Challenges Website**
  - Website provides information on grants and challenges related to air research and air sensors
  - https://www.epa.gov/air-sensor-toolbox/air-sensor-research-grants-and-challenges

3.6 Setup: Collocation and Correction

Air monitoring instruments need periodic checks to ensure they are functioning correctly and generating high-quality data. Environmental agencies, which are responsible for operating reference monitors, routinely **calibrate** the instruments by testing them with certified and known concentration standards. They then use the **calibration** results to adjust the instrument settings to match the certified or known concentration. This process is regularly repeated and monitored to ensure highly accurate data.

What are Some Commonly Used Terms for Reference Instruments?

- Reference Monitor
- Federal Reference Method (FRM)
- Federal Equivalent Method (FEM)
- FRM/FEM Monitors

Air sensors also need periodic checks but often cannot be calibrated in the same way as reference monitors. Instead, many air sensors are **collocated** or operated side-by-side with a reference monitor to see if they produce comparable data. Instead of adjusting instrument settings, which is often not possible for sensors, the raw data produced by a sensor may need to be adjusted (such as applying a multiplier and additive factor to the sensor raw data) to improve accuracy. This data adjustment, also called a **correction**, allows the sensor data to better match the reference monitor data. The ***Collocation-Correction*** process of collecting data and adjusting sensor measurements is described in the following sections.

What are Key Definitions Related to the Collocation-Correction Process?

Calibration – procedures for checking and adjusting a reference instrument's settings so that the measurements produced are comparable to a certified standard value.

Collocation – checking the performance of an air sensor by installing and operating the air sensor close to a reference instrument.

Correction – adjusting air sensor data to increase its accuracy relative to a known reference value.

****Important Note:** Sometimes these terms are used interchangeably but they have different and distinct meanings.

3.6.1 Air Sensor Collocation

Collocation involves checking the performance of an air sensor(s) by placing it near or beside a reference instrument and operating them at the same time and place under real-world conditions. Collocations may take place at existing air quality monitoring sites around the U.S. but require developing relationships with tribal, state, or local air monitoring agencies who may have varying constraints for allowing collocations (e.g., space or power limitations, access requirements, liability issues). Alternatively, it may be possible to work with academic partners or contractors to set up and operate a reference instrument specifically for your project. Be sure to follow established quality control and assurance procedures when operating the reference instruments. Ideally, sensors would be setup within about 20 meters of horizontal distance and 1 meter or vertical distance from the reference instrument. However, air flow to the reference instrument and sensors must be unobstructed.

As shown in Figure 3-9, a range of potential collocation options exist to meet various logistical and budgetary constraints. A combination of approaches can be used depending on the length of the project, the desired data quality, and other project constraints or needs.

What if a Reference Instrument is Unavailable?

Dependent on resources, it is possible to work with an experienced partner to setup and operate a reference instrument.

Alternatively, all sensors can be collocated together even without a reference instrument to better understand how well their measurements compare. With this information, you can conduct an air monitoring study making comparisons within your network of sensors. But, you'll have less confidence in the concentrations reported and be less able to compare results with other studies or data sources.

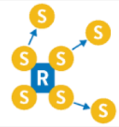
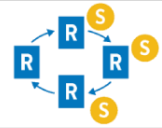
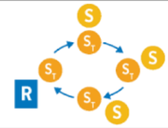
Key	Collocation Strategy			
S sensor R reference instrument S_T sensor transfer				
✓ yes ~ somewhat X no $ cost 🔧 maintenance	**Periodic All Sensors** All air sensors operate next to a reference instrument for short periods before and after the study and/or periodically.	**Continuous Subset** Some air sensors are continuously operated next to a reference instrument while others are deployed to other locations.	**Reference Transfer** A reference instrument visits each air sensor for a short period(s).	**Sensor Transfer** An air sensor collocated with a reference instrument, with known performance characteristics, visits each sensor location for a short period(s).
Continually check sensor performance	X	~	X	X
Capture a wide range of weather & pollution conditions	~	✓	~	~
All sensors tested at the same time	✓	~	X	X
All sensors tested against reference instrument	✓	✓	✓	X
All sensors tested at their sites	X	X	✓	✓
Additional equipment costs	$	$	$$$	$$
Frequent operator maintenance	🔧🔧	🔧🔧	🔧🔧🔧	🔧🔧🔧

Figure 3-9. Different Types of Air Sensor Collocation Strategies

Periodic All Sensor Strategy. All sensors are collocated with a fixed reference instrument at the beginning and end of the monitoring study. Depending on the length of the study, the collocation may happen periodically (e.g., seasonally, every 6 months, annually) throughout the study.

Strengths:

- All sensors are tested at the same time letting you know how they compare.
- All sensors are compared to a reference instrument for a limited time.
- There are no additional equipment costs if you can use an existing reference instrument.
- Sensors from smaller networks can be moved without major effort.

Weaknesses:

- Weather and air pollution conditions during the collocation may not be representative of the actual conditions encountered by the sensors when deployed at their sites.
- It will be more difficult to detect subtle changes in sensor performance over time or changes in performance due to a unique or short-term pollution events (e.g., short-lived seasonal dust storm) because a sensor is not permanently located next to the reference instrument.

- Moving sensors back and forth between the collocation site and their permanent sites can be labor intensive and increase the likelihood of damage.
- For large networks, there may not be enough space or power available at the collocation site for all of the sensors to be collocated at once.

Continuous Subset Strategy. All sensors are first collocated at a reference site. Then, some sensors are continuously operated next to a reference instrument while others are deployed to a different location(s).

Strengths:

- Because some sensors remain collocated with a reference instrument, sensors are tested under a wide range of weather and pollution conditions and you can detect performance changes over time. However, this approach assumes that all sensors perform similarly to one(s) that are continuously collocated.
- All sensors are tested at the same time letting you know how they compare.
- All sensors are compared to a reference instrument; some only for a limited time.
- There are no additional equipment costs if you can use an existing reference instrument.
- Sensors from smaller networks can be moved without major effort.

Weaknesses:

- Moving sensors between the collocation site and their permanent sites can be labor intensive and increase the likelihood of damage.
- For large sensor networks, there may not be enough space or power available at the site for all of the sensors to be collocated at once.
- If the collocated sensor fails and needs to be replaced, you no longer know how the new sensor's performance compared to the other sensors in the network. You might consider leaving several sensors collocated with the reference instrument.

Potential Modification:

- Space and power constraints may dictate that not all sensors can be collocated at the reference site at once. Alternatively, sensors can be collocated in batches. Or the sensors can be collocated elsewhere to understand how the sensors compare to one another and only the small subset then goes on to be collocated at the reference site.
- A sensor network may grow with time or portions of the network may need to be replaced due to sensor age. In these cases, batches of sensors could be collocated just before the network is expanded/replaced.

Reference Transfer Strategy. A reference instrument visits each sensor for a short period of time. This strategy can be useful for characterizing the performance of a network of sensors over the course of the long-term study.

Strengths:

- All sensors are compared to a reference instrument for a limited time; both the sensor and reference instrument experience the same pollution sources and concentrations and weather conditions during collocation.

- Sensors do not need to be moved to another location after their initial deployment, thereby minimizing the chances of damage.

Tip: Collocate sensors in a setting similar to where they are deployed

Make sure that the collocation site has similar characteristics to where the sensors are deployed. For example, do not collocate sensors near a road and then apply those results to a sensor network in a rural area.

Weaknesses:

- Weather and air pollution conditions or sensor performance may change between collocation periods.
- Does not test all sensors at the same time, under the same conditions.
- Can be costly to obtain, operate, move, and maintain a reference instrument(s).
- Some sensor sites may not be able to accommodate a collocated reference instrument (e.g., the sensor is mounted on a pole or in an unsecured area).

Sensor Transfer Strategy. A sensor, or research grade instrument, with known performance characteristics, is brought to each location where a sensor is deployed. In order to best know the sensor performance characteristics, sensors used in this strategy are usually left collocated with a reference instrument when not being moved around the network.

Strengths:

- All sensors are compared to a sensor or research grade instrument with known performance for a limited time; both experience the same pollution source and concentrations and weather conditions during collocation.
- It is less costly and labor intensive to transport a sensor or research grade instrument around the network.

Weaknesses:

- Assumes that the performance of the traveling sensor or research grade instrument does not change when moved from site to site which may not be true if pollution sources or concentrations change.
- Difficult to detect subtle changes in performance over time.
- The deployed sensors are not tested against a reference instrument, which makes it more difficult to quantify the accuracy of each sensor.
- Sensors are not tested at the same time, so you cannot determine how one sensor compares to another.

Collocation involves some critical questions to consider such as:

1. What reference instrument should I use?
2. How frequently should I collocate the sensors? Continuously (e.g., every day) or periodically (e.g., different seasons)?
3. How long should I collocate the sensors to measure enough variation in the full range of weather conditions (e.g., T, RH), and the full range of pollutant concentrations?
4. Should I collocate all sensors simultaneously at one central location or move a reference instrument to each air sensor site (i.e., test each sensor in its surroundings)?
5. Where should I collocate sensors so that the location resembles my sensor deployment area?
6. How much effort and what type of equipment (or access to it) is involved?

Some general tips for collocation include:

- **Collocate for an adequate number of days** to characterize a sensor's response over a range of weather and pollutant concentration conditions. Some suggested number of collocation days for data collected at different time intervals include:
    - 24-hour data: About 30 days of collocation
    - 1-hour data: About 14 days of collocation
    - 5-minute data: About 7 days of collocation
- **Locate the sensor as close to the reference instrument as possible** so that the devices are measuring the same air quality. If you are using an existing air quality monitoring site, you will need to work closely with your tribal, state, or local environmental agency to access their reference instruments and data repository. Keep in mind that some agencies may not allow the general public to collocate sensors at their sites.
- **Measure meteorological conditions** (T, RH, wind speed, wind direction) because the sensor performance may be affected by weather conditions. The tribal, state, or local, environmental agency may measure these at their air monitoring site. Measurements may also be available from a nearby airport or national weather service or similar data service.
- **Consider using analytical tools** to help you evaluate your collocation data (e.g., U.S. EPA's Macro Analysis Tool).

Tip: Collocate sensors during different times to understand the full range of environmental conditions

If you cannot capture the full range of conditions (e.g., full range of temperatures) from one collocation period, plan to re-check at a different time.

See U.S. EPA's Air Sensor Collocation Guide for additional information.

3.6.2 Correction of Sensor Data

The collocation results can be used to **correct** the sensor data to more closely match the data from the reference instrument. This **correction** process helps account for known bias and unknown interferences from weather and other pollutants and is typically done by developing an algorithm. An algorithm can be a simple equation or more sophisticated process (e.g., set of rules, machine learning) that is applied to the sensor data. This section further discusses the process of **correcting** sensor data.

The first step in correcting sensor data is to compare the collocation data obtained from the sensors and reference monitor, making sure to align the sampling times and averaging periods for the two data sources. Be sure to note the time zones and whether daylight savings time is used. For example, to compare 1-minute air sensor data to 1-hour reference data, users will need to calculate a 1-hour average of the sensor data (i.e., the average of 60, 1-minute values). Users should ensure that the averaging methods match for both sensor and reference data. Averages may be time-beginning (e.g., a 1-hour average computed from measurements collected between 12:00 and 12:59 is assigned to the 12:00 hour) or time-ending (e.g., a 1-hour average computed from measurements collected between 12:00 and 12:59 is assigned to the 13:00 hour).

Sensor and reference monitor data can be compared by creating a scatter plot to visualize the relationship. Figure 3-10 shows an example scatter plots. In this Figure, data from the reference instrument, in this case the T640x, is shown along the horizontal x-axis and sensor data is shown on the vertical y-axis. Each dot shown in the Figure represents a measurement taken at some point in time. By drawing lines vertically and horizontally from each dot, you can find the reference concentration and sensor concentration reported at each time interval. If the sensor and reference measurements perfectly agreed with one another, all of the dots would lie along the 1:1 line shown in grey. Often, there is disagreement and you find that the sensor may always measure a little higher or lower than the reference instrument. This disagreement is called bias (see *Section 3.4.1*) and sometimes an algorithm can be created to correct the sensor data and eliminate the bias.

You may see that the dots cluster along a line or curve. If so, it may be possible to create an algorithm or equation that describes the relationship between the air sensor and reference data. The most common, and often suitable, correction equation is the ordinary least-squares linear regression equation. A function for determining a linear regression equation is well established in many software packages (e.g., Excel, R) and available using the U.S. EPA Excel-based Macro Analysis Tool as well.

What is the Ordinary Least-Squares Regression Equation?

A common correction algorithm is the "best-fit" line equation derived using the **ordinary least-squares regression**:

y = mx + b

Where:

y = the sensor measurement

m = the slope of the regression line

x = the reference monitor measurement

b = the y-intercept of the regression line

Slope (**m**), which can be positive or negative, shows how similar the sensor measurements are to the reference measurements. The closer "m" is to 1, the more the sensor responds like the reference instrument. **Intercept** (**b**) shows what the sensor measurement will be, on average, when the reference instrument measures zero concentration. Together the intercept and the slope describe the sensor **bias.**

Linear regression equations also include the **coefficient of determination** (**R^2**), ranging from 0 to 1. R^2 measures the amount of data scatter and how closely the data points are to the "best fit" line. R^2 values nearer to 1 indicate stronger correlations or less data scatter.

In Figure 3-10 panel A, the slope is > 1 (m = 2.02) and sensor measurements are higher than reference monitor measurements when concentrations are above 8.5 μg/m³. This is an example of a sensor that overestimates pollutant concentrations. In panel B, the slope is < 1 (m = 0.22) and all sensor measurements are less than the reference monitor measurements. This is an example of a sensor that underestimates pollutant concentrations. A slope equal to 1 would indicate perfect agreement between sensor and reference data.

A measure of how close the data points are to the slope-intercept line, represented by R^2, is the called the coefficient of determination. This value describes the amount of scatter in the data.

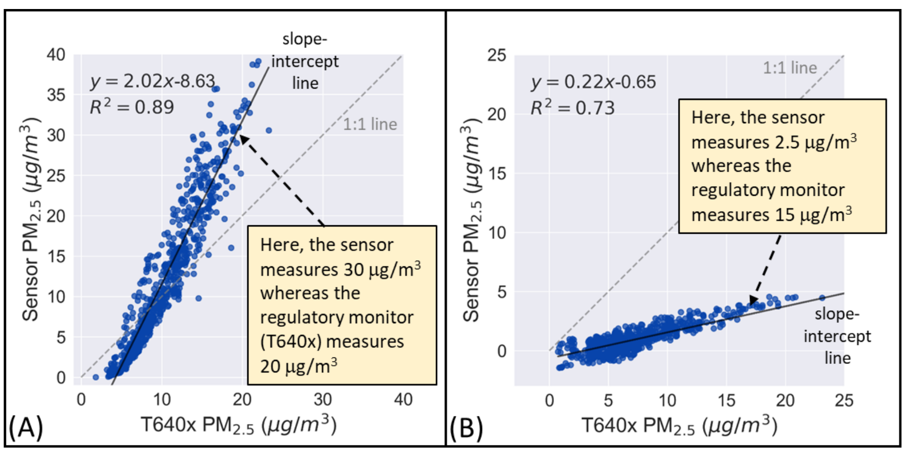


Figure 3-10. Example of the Ordinary Least-Squares Regression

R^2 ranges from 0 and 1, where values closer to 1 indicate stronger correlation, or agreement, between the sensor and reference data. A value closer to 0 indicates a lack of agreement.

Some sensors, like the example shown in Figure 3-11, may not show strong agreement with the reference instrument (R^2 closer to 0). Sometimes scatter plots look like a scatter of points rather than a grouping of points that resemble a line. This often means that an ordinary least-squares linear regression equation is not appropriate for correcting the sensor data. This can mean that the data is not correctable or useable but, sometimes it can mean that a more complex algorithm or equation may be needed. For instance, a user may choose to apply a multi-linear regression because the sensor response is related not only to pollutant concentration but also another variable like RH or the concentration of another pollutant. Developing correction algorithms is an active research area with new approaches and methods likely to evolve over time. Some research has applied multi-linear regressions, polynomial fits, more complex models, and even machine learning. Understanding the correction algorithm is essential for ensuring traceability from raw to corrected data and for understanding the factors that influence the measurement. Complex or "black box" algorithms may sound promising, but often simple, understandable algorithms are preferred.

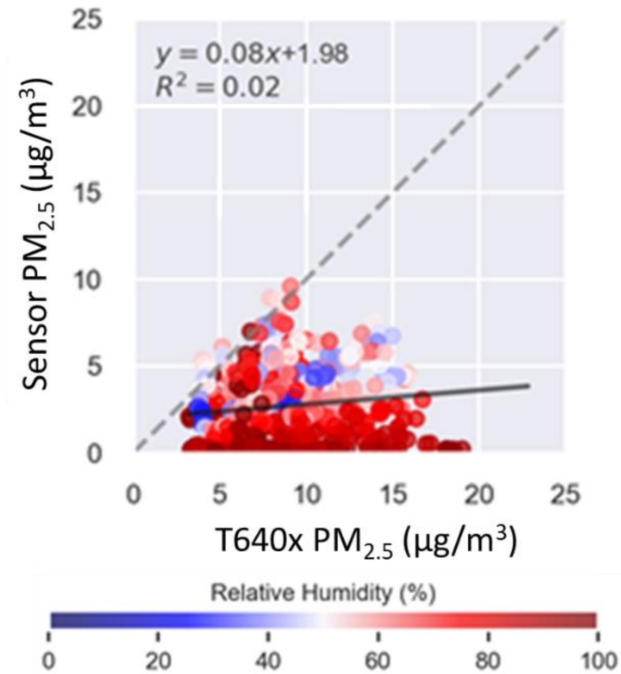


Figure 3-11. Example of a Sensor That Shows No Agreement with the Reference Instrument

Note that an air sensor may respond differently over the full concentration range. For example, Figure 3-12 shows a linear response relative to the reference data at lower concentrations and a non-linear response above this concentration. Thus, a single type of correction equation may not apply over the full range of concentrations.

> **Are There Other Metrics That Describe Sensor Performance?**
>
> Error is a measure of the disagreement between the pollutant concentrations reported by the sensor and the reference instrument (see *Appendix F*).
>
> Several metrics are used to describe error including Root Mean Square Error (RMSE), Mean Bias Error (MBE), and Mean Absolute Error (MAE), among others. Each metric has a slightly different definition and calculation.

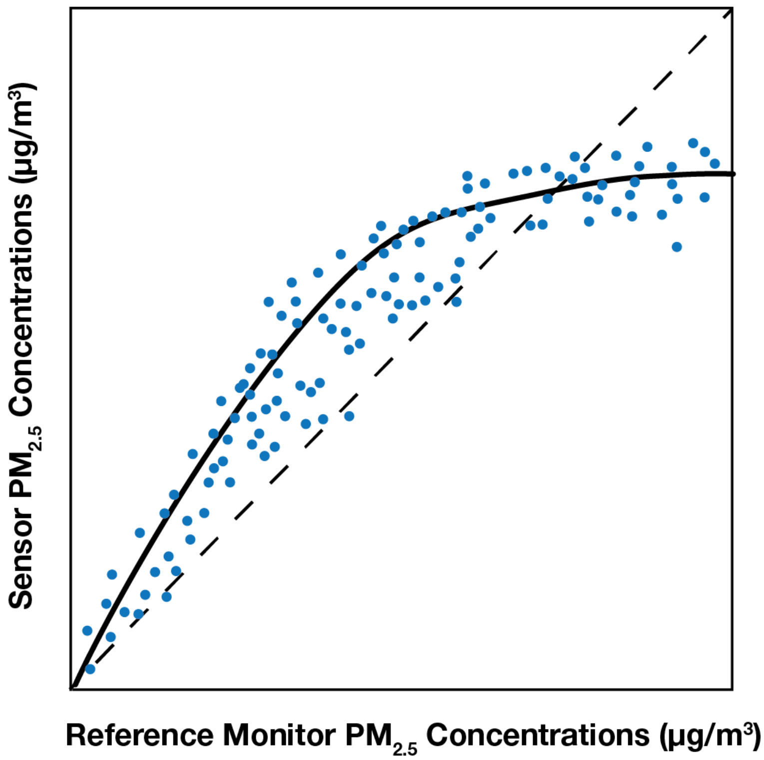


Figure 3-12. Scatter Plot Showing that an Air Sensor has a Linear Response at Lower Concentrations and a Non-linear Response at Higher Concentrations

Figure 3-13 presents an example correction using a linear regression equation derived from sensor and reference data. In this example, the corrected sensor measurements are obtained by rearranging the "best fit" line equation (i.e., y = mx + b) to solve for "x", where "x" equals the corrected sensor measurement. Users can correct sensor data using the algorithm so that it more closely matches the reference data. Note that some sensor manufacturers apply data corrections on-board the sensor or in the cloud. Also, some data management systems (see *Section 3.7.3*) can apply a correction. In either of these cases, it is good practice to ask the manufacturer about any corrections performed on the data and to fully understand how the air sensor data are corrected.

$$Corrected\ Sensor\ Data = \frac{Measured\ Sensor\ Data - b}{m}$$

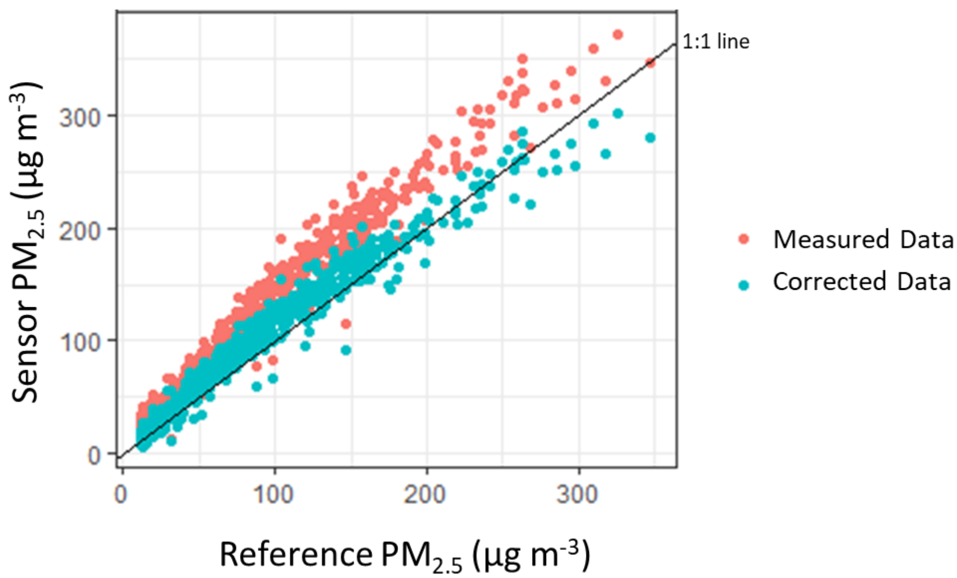


Figure 3-13. Examples of Air Sensor Data Corrections

Sometimes scatter plots may resemble the examples shown in this section but have just a few data points that appear far away from the linear regression line. These points are referred to as **outliers**. Sometimes these data points can significantly change the results and instead of the linear regression line passing through the middle of most of the data points, it can seem to move off to one side. This indicates that those suspected outliers should be investigated a little further before interpreting the results. Creating a **time series plot**, or a plot of the sensor and reference instrument concentrations as a function of time, may show **data spikes** (data points with higher concentrations) from one or more of the instruments. Users may want to examine these spikes to consider if they are real or not. Some spikes may represent elevated pollutant concentrations outdoors. For instance, particulate matter (PM) concentrations may go up for a short period of time because of nearby mowing activities. Other spikes may not reflect real changes in pollutant concentrations and may instead indicate that something is wrong with the device like a data logging or device error. If the spikes are believed to be false, users may consider if there is a routine way of detecting and removing the false data that will not accidentally remove the good data. If a routine method can be developed, it should be documented or written out so that the method can be communicated, and all data will be treated similarly. Using a routine method to identify and remove false spikes is a processed commonly called data **cleaning**. After cleaning the data, the linear regression can be recalculated and applied to the remaining data to complete the data correction.

Resources for More Information

- **U.S. EPA Air Sensor Collocation Instruction Guide,** U.S. Environmental Protection Agency, Office of Research and Development

- Resource provides background information, links to web-based supporting materials, and instructions for evaluating the performance of air sensors by comparing the measurements made by collocated sensors and reference instruments
    - https://www.epa.gov/air-sensor-toolbox/air-sensor-collocation-instruction-guide

- **U.S. EPA Air Sensor Collocation Macro Analysis Tool**
    - Excel-based tool that helps users compare data from air sensors to data from reference instruments
    - https://www.epa.gov/air-sensor-toolbox/air-sensor-collocation-macro-analysis-tool

- **Community in Action: A Comprehensive Guidebook on Air Quality Sensors,** South Coast Air Quality Management District (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC), September 2021
    - Guidebook for community organizations that covers planning for monitoring using sensors; sensor deployment, use, and maintenance; and data handling, interpretation, and communication
    - http://www.aqmd.gov/aq-spec/special-projects/star-grant

- **South Coast AQMD Low-Cost Sensor Data Analysis Guide**
    - Guide that provides some brief instructions to help community scientists interact with the data they are collecting as well as some questions to help guide their analysis
    - http://www.aqmd.gov/docs/default-source/aq-spec/star-grant/air-quality-sensor-data-analysis-guide.pdf?sfvrsn=6

3.7 Collect: Data Collection, Quality Assurance/Quality Control, and Data Management

With a question well-posed, a plan created, and sensors properly set up after collocation, it is time to collect data. There are many activities involved in data collection beyond simply turning on the sensor and collecting measurements. Users will need additional preparation before and during data collection activities to ensure that useful data are collected.

This section discusses various data collection activities, quality assurance/quality control (QA/QC) checks, and typical components of data management systems (DMSs).

3.7.1 Data Collection Activities

Collecting good quality, complete, and ultimately useable data will require attention to several oversight tasks after the air sensors begin operating. These tasks include:

Frequent data review. Reviewing data frequently (e.g., daily, weekly) lets you detect problems early, notice trends in the data, ensure that maintenance activities are completed, and become familiar with recurring patterns. For instance, plotting the data, whether in a time series (i.e., a plot with the pollutant concentrations on the y-axis and the date and time on the x-axis) or another form can be a good place to start (see *Section 3.8* for plotting options). You might see typical patterns, such as low concentrations during the morning hours or identify when high pollution episodes occur. These data reviews help you develop a general sense of air quality in an area under different conditions. When typical conditions are known, it becomes easier to identify times when sensor readings are atypical and why these atypical readings are occurring (e.g., Is an air sensor malfunctioning? Is wildfire smoke present? Is a weather pattern responsible for higher levels?).

What are the Benefits of Frequent Data Review?

- Identify and resolve problems quickly
- Minimize data loss
- Learn what normal patterns look like
  - Detect real, high-pollution events early
  - Understand how air quality changes:
  - During the day
  - Weekend vs. weekday

Maintenance. Like most other forms of technology, air sensors require preventive maintenance to ensure proper functionality and reliable data collection. Maintenance activities are necessary for both short- and long-term operations. Air sensor maintenance can include regularly scheduled cleaning of surfaces or inlets to prevent the buildup of bugs or dust, replacing filters, or replacing sensor detector components as they age. Maintenance can also include examining site conditions for any changes (e.g., vandalism, overgrown trees).

By properly maintaining an air sensor device, you can reduce errors in data collection, extend the device's operating life, and save money that would otherwise be spent on replacement parts and repair services. Typical air sensor maintenance activities are listed in Appendix C and may also be provided by the manufacturer.

Troubleshooting. Problems with air sensors (e.g., failing to report data) will likely occur and may require troubleshooting to resolve the problem and to continue collecting data. Troubleshooting might include visiting the sensor, contacting the manufacturer, seeking guidance from other air sensor users, or other activities. User manuals may also provide tips on troubleshooting.

Quality control (QC) checks. It is important to frequently review the data for problems such as outliers (e.g., data that are significantly different from other data values), drift, etc. Some sensor manufacturers may offer a software package or online user interface that offers some automated checks of the data to assist in this process. Note that automated checks may not catch subtle problems (e.g., a gas sensor slowly degrading and losing its response) or may flag a real-life event or very high concentrations (e.g., high $PM_{2.5}$ concentrations from wildfire smoke) as bad data. Do not solely rely on automatic QC checks to identify issues with the data—always review the data frequently. Section 3.7.2 discusses additional QA and QC checks.

Periodic collocation. Collocation can help quantify the accuracy of a sensor while periodic checks can help ensure that accuracy is not changing over time or in different conditions. Users should develop a collocation approach or use the manufacturer's recommendation to conduct a periodic collocation to check the quality of the air sensor's measurements. Section 3.6 provides information on the process of collocation and how to correct data to make it more accurate.

3.7.2 Checks to Ensure Quality Assurance and Quality Control

Quality assurance (QA) and **quality control** (QC) are essential components of a project that will ensure that credible and useful data are collected (Figure 3-14). QA consists of planned steps to manage the project and collect, assess, and review the data. An example of QA is developing a plan for air monitoring (see Section 3.3) to ensure identification of all tasks or steps to review air sensor data and confirm the sensor is operating properly. *QC* includes steps taken to reduce error from the instruments or measurements during a project. QC procedures are activities that include collocation, correction of data, maintenance, automatic data checks, and data review. Essentially, QA is the planning and QC is the action taken to produce high-quality data. QA/QC are important components of a project that will help ensure that credible and useful data are collected.

Regardless of whether the user presents the results as a written report, oral presentation, or in conversation, users should clearly describe the approach, the measurements obtained, the QA/QC checks in place, and the interpretation of the data. If any of these components are missing or not well executed, your data's credibility will diminish.

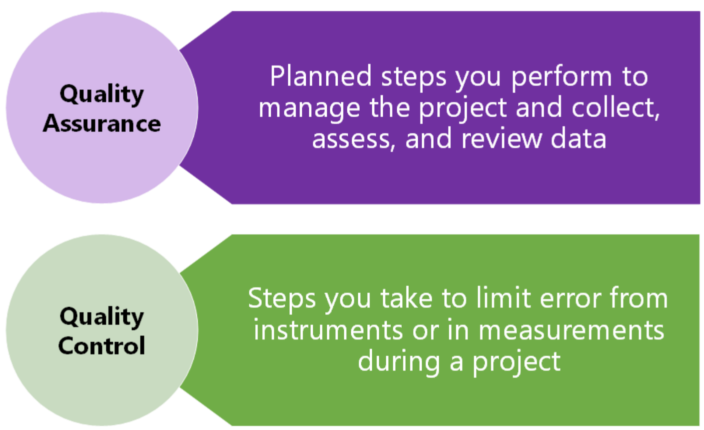


Figure 3-14. Definitions of Quality Assurance and Quality Control

Table 3-2 shows the recommended QC checks that can be performed on an air sensor and its data. The checks are designed to catch problems early, correct them, and produce a useful, high-quality data set.

Tip: Check sensor data and compare to nearby reference data after setup, and review data frequently.

Issues with reporting time and units in data files are common problems that can be identified by checking the data as soon as air sensors are set up and reporting measurements. Also, immediately after setup, users should carefully review and compare the data collected against nearby reference instruments to ensure the data appear reasonable. It is highly recommended that users review data frequently (e.g., daily, weekly) to identify problems quickly and to determine if the data are normal or abnormal.

Table 3-2. Common Quality Control (QC) Checks

QC Check	Description
Units	Check that the sensor reports data in the correct units of measure.
Time	Check that the sensor reports data at the correct time and in the right time zone. Check times after any seasonal time changes (e.g., daylight savings time).
Timestamp	Determine the timestamp, which is the time when data are stamped (i.e., tagged) by an instrument. Measurements and data averages will have times that either represent the beginning of the time period (time beginning) or the end of the period (time ending).
Matching Timestamps	Check the time zones and timestamps for each dataset to make sure they are similar when comparing measurements made by different instruments.
Data Review	Check data frequently (e.g., daily, weekly) to detect problems early, identify trends in the data, ensure that maintenance activities were completed, and become familiar with recurring patterns (see *Section 3.7.1*).
Data Completeness	Completeness measures the amount of data a sensor collects compared to the amount of data that was possible to collect if the sensor operated continuously, without data outages, during a period (e.g., 1-hour, 1-day). A 75% completeness level is a useful criterion to meet as the averaged data is generally representative of that time period. For example, at least 45, 1-minute measurements are needed to make a valid 1-hour average at 75% completeness.
Automatic Data Checks	Software can check data for problems and outliers. Check your data management system for these and other data checks. Note that some data checks may not catch subtle problems (e.g., a gas sensor degrading and slowly losing its response) or may flag an infrequent event or very high concentrations (e.g., high $PM_{2.5}$ concentrations from wildfire smoke) as bad data. Do not solely rely on automatic QC to check data quality; always do frequent manual data reviews. Common automatic checks include: • **Range**. Check the minimum and maximum concentrations expected and recognize some air sensors may report slightly negative values. • **Rate of Change**. Check the difference in data values from an air sensor between two consecutive time periods (e.g., hours). Flag the data if the difference, or rate of change, exceeds the value set by the user. For example, it is unusual for $PM_{2.5}$ concentrations to jump by more than 100 µg/m^3 from one hour to the next unless a significant source such as wildfire smoke or fireworks is present. Thus, if the

QC Check	Description
	value for the rate of change check is set to 100 µg/m^3, an increase from 70 µg/m^3 to 200 µg/m^3 between consecutive hours would exceed the rate-of-change check. • **Sticking**. Check if data values are "stuck" at the same value for a specified number of hours. Establish criteria for the number of consecutive hours for which data can be reported at the same value. For example, it is uncommon for PM_{10} concentrations to remain at the same concentration for several consecutive hours. If the number of concentration hours is set to three, and the PM_{10} concentration is the same value for more than three consecutive hours, that could indicate a stuck value. • **Duplicate sensor comparison.** Some sensors incorporate two identical sensing components inside which provide two separate pollutant concentration measurements. Check the agreement between the readings and flag data if the difference exceeds an acceptable threshold. • **Buddy System**. Check the difference between data values obtained from a single location and the average data values obtained from other nearby locations. • **Parameter-to-Parameter**. Check two or more pollutants for known or expected physical or chemical relationships. For example, $PM_{2.5}$ should be less than PM_{10} measured at the same site and time, and NO_2 and O_3 concentrations are often inversely correlated (i.e., when O_3 is high, NO_2 is typically lower).
Manual Data Validation	Evaluate the data quality during the collection phase of the project to identify and correct potential problems that may arise. To accomplish this, analyze data to identify seasonal, day/night, and weekday/weekend patterns and weather changes. An absence of expected patterns may indicate a problem with the sensor or with the measurement approach.

Many of the QC checks in Table 3-2 will help evaluate the quality of the data obtained during the collection phase to identify and fix common problems found in air sensor data. Common problems in the data are described below.

- **Drift** refers to a gradual positive or negative change in a sensor's response over time due to various reasons (e.g., aging of the sensor component). Drift may lead users to incorrectly conclude that concentrations have increased or decreased over time. Some ways to reduce drift include frequently performing a collocation-correction process (see *Section 3.6*) or conducting frequent maintenance on the sensor.
- **Interferents and Influences** include factors that hinder, obstruct, or impede the sensor's ability to provide high quality measurements. Other pollutants that interfere with the measurement of the target pollutant are sometimes referred to as cross-sensitivities. For example, oxidants (e.g., O_3) in the air can interfere with electrochemical sensors used to measure NO_2 and high moisture content (e.g., above 85 percent RH) can cause PM air sensors using optical technologies to overestimate PM concentrations. Debris, dirt, and insects can also impact sensor performance. Interferents and influences may alter sensor accuracy, and a sensor

can be impacted by several different factors simultaneously. Manufacturers sometimes disclose which pollutants and weather conditions may impact sensor performance, but manufacturers may not describe how much the sensor will be affected. Before using a sensor to measure air quality, consider whether the possible sensor interferents will be present in the air to be sampled and check with the manufacturer about potential interferences and how to minimize their effects, if possible.

- **All measured parameters may not be reported** in a dataset**.** Many sensors report several pieces of data including pollutant concentration(s), temperature (T), relative humidity (RH), and more. Because data may come from several components within the device (e.g., pollutant concentration come from one component, T/RH from another), it is possible pieces of the data stream may be missing while others are present. Be sure to review each parameter separately to ensure all components are reporting properly.
- **Unexpected downtime** due to for example, power loss and power surges, can affect air sensor performance by causing sensors to shut down, restart, or interrupt data transmission. For example, an air sensor that has a longer warm-up period may show data gaps or inconsistent data when power loss occurs. Data gaps and significant data loss associated with unexpected downtime may prevent users from collecting a complete, valid data set.
- **Unexpected problems** can occur in many monitoring instruments, air sensors, and other electronic equipment. In some cases, a concentration spike (e.g., data spike, outlier) may be caused by electronic or other device-related issues; however, a spike could be a valid measurement and it can sometimes be difficult to tell the difference. Local observations may help to interpret the data. For example, observing someone smoking near a PM sensor and a seeing a corresponding short-term increase in PM concentrations would indicate that this is a valid measurement (i.e., the sensor responded to the smoke), even though the measurement does not represent the general air quality conditions at that time.

How do I Verify That my Sensor is Working Properly if There are No Reference Monitors Nearby?

Although we recommend that users carefully review and compare the sensor data collected against nearby reference instruments to ensure the data appear reasonable, there are situations and locations where this comparison is difficult because there are no reference monitors nearby.

Based on resources (e.g., money, equipment, expertise), users could

- Setup a reference instrument nearby
- Setup a sensor which was recently collocated with a reference monitor and shown to provide comparable results
- Compare trends and concentrations with several nearby sensors and consider whether similarities/differences are expected or surprising.

In summary, having QA/QC checks in place for a project is important as they help ensure data quality and allow you to address common problems if they arise. Having QA/QC information available is also important if it is requested by anyone who wants to use the data.

3.7.3 Data Management System

Air sensors produce a large amount of data that must be routinely tracked and managed to access, review, and use the data effectively. A data management system (DMS) is a collection of procedures and software needed to acquire, process, and distribute data. A DMS helps streamline data processing, provides QC and review tools, maintains digital records and backups of the data, and displays, reviews, and facilitates sharing the data. These features make it easier to use air sensor data and to identify instrument errors or other problems early. A DMS also makes it easier to operate and manage a network of multiple sensors simultaneously.

Figure 3-15 shows the key components and functions of a DMS. Note that a DMS may be bundled with a sensor (e.g., manufacturer offered cloud data portal), purchased as a third-party system, or be available as open-source software. Each of the functions shown in Figure 3-15 play an essential role in operating either a single sensor or network of air sensors and collecting useful data.

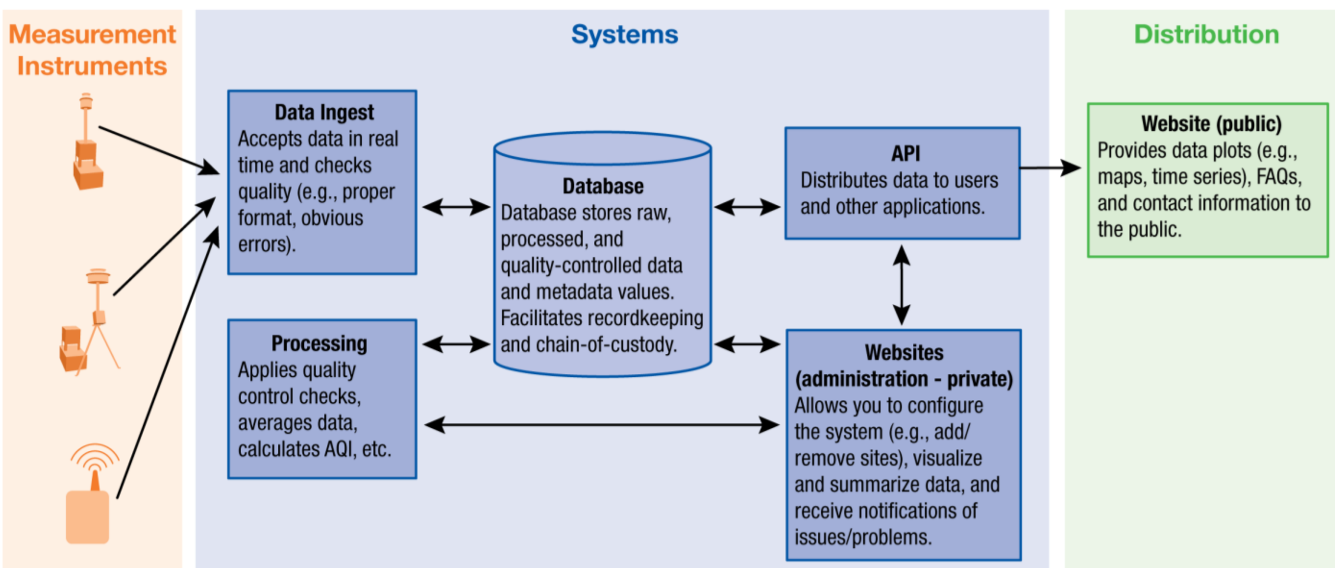


Figure 3-15. Major Components and Functions of a Data Management System (DMS)

The basic DMS functions consist of the following:

- **Ingest data**. A DMS acquires and reformats data. The DMS can either pull data from an air sensor system or sensors can push data to the DMS. Think carefully about data format as these choices can impact data storage volume and how easy it is to use existing code to process and visualize the data.

- **Store data and metadata**. After acquiring and reformatting data, the DMS needs to store data and metadata (e.g., site locations, configurations, unit identifiers). The storage system could be a spreadsheet, a file-based system, or a relational database (i.e., database structured to recognize relations among data). These options provide different levels of flexibility and scalability and may or may not require a license agreement. Storing data can also include tracking changes to the data and metadata (i.e., chain of custody) to help ensure data integrity.
- **Process data.** After collected data are stored, the DMS needs to process and QC data. This consists, for example, of applying data correction algorithms, creating data averages (e.g., 1-hour, 8-hour, 24-hour), calculating summary statistics, converting data to an Air Quality Index (AQI) for health messaging, or other data processing and visualization needs. QC checks (see Table 3-2) are a necessary part of data management and should be included to identify outliers and problems with the data.
- **Monitor network health.** Features that help you quickly and easily identify problems within a network of sensors are highly desirable especially when your network consists of many sensors or when sensors are spread out over a large geographical area. At a minimum, this feature should help identify sensors that are not reporting data so that they can be repaired or replaced. More advanced features may identify sensors that often fail the QC checks (see Table 3-2) or even help diagnose problems for faster troubleshooting or repair (e.g., pinpoint the external component that needs to be replaced).
- **Control of the system**. It is highly useful for users to have the ability to control the DMS. System control features might include the ability to change system settings (e.g., add/remove sites or users, change time zones), set or change QC criteria, edit and correct data, generate statistical summaries and reports, and visualize data. These types of control features enable users to oversee and adjust the DMS to meet project needs.
- **Distribute data**: Retrieving and distributing the data is another important function of a DMS. These activities can range from very simple ways to export data to more sophisticated software called **Application Program Interfaces (APIs)**. An API allows interactions between the DMS and other remote software systems. The API defines the kinds of calls or data requests, how to make them, the appropriate data formats and conventions to follow, and so on. The API also allows other websites and data systems on the internet to access data within the DMS.

Other recommended features of a DMS include:

- **Data security**. The ability to keep data safe from hacking, altering, or other unwanted activities is important for data integrity.
- **Data redundancy (backups)**. Given the potential for situations that can cause data loss, data backups are critical to ensure that users can recover data.
- **Cloud-based software that can be accessed from any location**. It is ideal to have software that can allow users to view data and/or instrument status remotely no matter where a user is located. This will allow users to check monitor instruments for

any problems, change instrument settings if needed, frequently review data, or carry out other activities to manage a project.

- **Version control features for tracking changes to the data**. Manufacturers may change the firmware or other settings on a device that can impact the data. Having a way to document these changes will allows users to better understand their data.
- **Data ownership terms and usage rights**. Detailed information about who owns the data, who has access, and if there are terms and conditions on its use will help users determine if the DMS is acceptable for their proposed project.
- **Tools for data QC, data review, and visualization**. These tools can allow users to frequently check the data to identify any issues and quickly look at trends in the data.
- **AQI calculations and formulas**. AQI may be calculated differently using different formulas. If users want to directly compare the AQI to the U.S. AQI, for example, knowledge on how the AQI is calculated is important.
- **Public website that includes data displays (e.g., maps, time-series plots, and tables), responses to frequently asked questions, and health information**. A public DMS can help communities quickly view data for trends, health information, and answer their questions about the data.
- **Email or text alerts for missing data, high values, and other events**. Instrument problems, air quality events, or other issues can always occur in a monitoring project. The ability to know when these events occur can help users troubleshoot and resolve issues during a project.

Tip: A DMS can add costs to a project, so budget wisely

A DMS can be highly valuable for sensor project, but it is important to recognize that these systems can add additional costs to a project. Depending on the provider, pricing can vary and be a one-time, monthly, or annual fee. Having a good understanding of these costs and pricing plans is important.

Selecting a DMS that meets your current and future needs involves several considerations. First, consider the size of the network. The larger the network of sensors and volume of data generated, the greater the management challenge, and a DMS with automated procedures can help minimize effort. You will also need to consider security elements like who can access the DMS and other special information technology (IT) requirements such as the physical location of the cloud software. Some systems are easy to use, yet may not allow customization, while others are fully customizable and require software programming experience. You will also need to consider your budget for software, licenses, and recurring (e.g., monthly) fees. Make sure to ask about fees associated with adding more network sites or parameters, and other cost drivers such as who will be responsible for customizing and maintaining the software.

A range of options exist for a DMS based on your specific needs:

- **Spreadsheets** can be used as a DMS to handle a small amount of data collected over a limited time period. Although a spreadsheet is easy to create, it can be challenging to automate processes and scale the system for larger sensor networks.
- **Cloud-based systems** are widely available to handle data. Many large technology companies provide generic solutions to manage data. Although not always explicitly designed for air quality applications, these cloud-based systems offer many of the basic DMS functions discussed above; however, they may need to be customized to suit your needs.
- **Sensor manufacturer DMS solutions** are offered by some air sensor companies and perform the functions shown in Figure 3-15. In addition, systems offered by some companies can ingest data from other sensor and reference monitors. You will need to assess the capabilities of their systems, understand how much customization is possible (if any), and consider any additional costs.
- **Commercial, air-quality focused systems** are used by many air quality agencies and other professionals that collect and manage air quality data. These systems are highly customized to meet the needs of air quality monitoring, and the vendors typically understand air quality concepts. Vendors usually charge a software license and/or recurring fee to use their DMS and additional features.
- **Open-source, air quality-focused systems** can provide another solution for data management. They may not have licensing costs, but there could be costs associated with hosting the software. This approach allows for scaling up as a sensor network becomes larger but may require experience with open-source software to install, operate, and customize the system.

Whichever DMS approach is used, consider the following best practices for data management:

- **Plan how you will manage** the data before deploying any air sensor – it takes considerable time and effort to manage the data.
- **Contact other organizations** that are operating air sensors or sensor networks and ask about what type of DMS they use and any recommendations they may have.
- **Check with the air sensor manufacturer/vendor** for DMS solutions they offer or if they can recommend other DMS solutions that are compatible with their products.
- **Check with your internal information technology (IT) department** before purchasing, contracting, or designing a DMS to ensure that it meets data security needs and that the correct settings can be enabled on networks and computers.
- **Look for an automated DMS** to streamline routine tasks (e.g., data ingestion, QC, data reporting).

Resources for More Information

- **AirSensor and DataViewer Tools (R package)**
  - AirSensor is an open-source R package that allows users to access historical data, add spatial metadata, and visualize community monitoring data through maps and plots
  - DataViewer is an interactive web application that incorporates the functionality and data plotting functions of the AirSensor for interpreting and communicating community data collected by sensor networks
  - https://github.com/MazamaScience/AirSensor/tree/version-0.5
  - https://github.com/MazamaScience/AirSensorShiny
  - These papers summarize the development and enhancements of the AirSensor and DataViewer tools:
    - Feenstra et al, 2020 https://doi.org/10.1016/j.envsoft.2020.104832
    - Collier-Oxandale et al, 2022 https://doi.org/10.1016/j.envsoft.2021.105256

- **Data Policies for Public Participation in Scientific Research: A Primer**, DataONE Public Participation in Scientific Research Working Group, August 2013
  - Guide that introduces data policies in the context of public participation in scientific research or community science, provides examples, and best practices for implementing data polices in community science projects
  - https://safmc.net/wp-content/uploads/2016/06/Bowseretal2013_DataPolicyPrimer.pdf

- **Handbook for Citizen Science Quality Assurance and Documentation**, U.S. Environmental Protection Agency, EPA 206-B-18-001, March 2019
  - Handbook that covers common expectations for quality assurance and documentation and best management practices to level the playing field for organizations that train and use volunteers in the collection of environmental data
  - https://www.epa.gov/sites/default/files/2019-03/documents/508_csqapphandbook_3_5_19_mmedits.pdf

- **Data Management Guide for Public Participation in Scientific Research**, DataONE Public Participation in Scientific Research Working Group, February 2013
  - Guide that provides best practices and other considerations for data management along the life cycle of community science projects
  - https://www.dataone.org/sites/all/documents/DataONE-PPSR-DataManagementGuide.pdf

- **USGS Guide to Data Management**
  - United States Geological Survey (USGS) website that provides guidance, best practices, and tools for data management including in-depth training modules and numerous data management example scenarios
  - https://www2.usgs.gov/datamanagement

- **Survey Report: Data Management in Citizen Science Projects**, Chade S and Tsinaraki C., Publications Office of the European Union, JRC101077, 2016
  - Report summarizes the findings from a Joint Research Centre (JRC) survey of community science projects completed primarily in European Union (EU) countries
  - https://publications.jrc.ec.europa.eu/repository/handle/JRC101077

- **Citizenscience.gov Website**
  - Government website that promotes crowdsourcing and citizen science across the U.S, government; website catalogs government supported community science projects, provides a toolkit to assist with project design and maintenance, and serves as a gateway for community science practitioners and coordinators across the government
  - https://www.citizenscience.gov/#

- **U.S. EPA Guidance on Environmental Data Verification and Data Validation**, U.S. Environmental Protection Agency, EPA/240/R-02/004, November 2002
  - Guidance document that specifies the agency-wide program for environmental data QA and includes practical advice to individuals implementing data verification and data validation
  - https://www.epa.gov/sites/production/files/2015-06/documents/g8-final.pdf

3.8 Evaluate: Analyzing, Interpreting, Communicating, and Acting on Results

Understanding air sensor data is as important as selecting and operating an air sensor. You should plan early for how to process, analyze, and interpret the data and how you will share and communicate the results. Do not wait until data have been collected to determine how you will use the data. Evaluating the results may reveal unanswered questions that revise or update your questions or other steps in your plan, as shown in Figure 3-1.

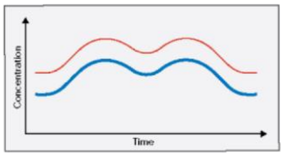
There are many methods to analyze, evaluate, and share results, but the choice of which approach to use depends on the questions you are seeking to answer. Some analysis and interpretation can be relatively simple, while others that involve complex evaluations and in-depth interpretation can be a challenge to communicate. For example, a $PM_{2.5}$ air sensor outside a home can measure local concentrations and help users determine the times of day when $PM_{2.5}$ levels are lowest. However, deploying an air sensor network consisting of many sensors to detect areas of higher or lower concentrations will require much more detailed data analyses and interpretation. Again, users should plan how they will analyze, evaluate, and communicate their results in advance. The remainder of this section provides guidance on methods and techniques for accomplishing these tasks and resources for getting started.

3.8.1 Analyze and Interpret Data

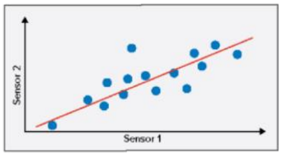
Data analysis is generally comprised of processing, then visualizing the data. Processing the data typically includes the following steps:

1. **Data cleaning** to prepare the data for analysis. Cleaning includes: a) QC checks and validation of the data to remove problems (e.g., large negative values, high values caused by sensor failure) and outliers, and b) checking timestamps and units.
2. **Documenting** any adjustments or changes to the data.
3. **Acquiring data from other sources** needed for the analysis. These data could include corresponding meteorological data, traffic data, emissions information, and/or other sources.
4. **Averaging data** to evaluate the "big picture" signals in the data.
5. **Grouping data** to summarize the data, or group or filter data to explore more details. Some examples include grouping data by time of day, day of week, location, and/or meteorological conditions.
6. **Correlating data** to begin evaluating the relationships between the air sensor data and other data values. For example, correlating $PM_{2.5}$ concentrations and wind speed can show how different weather conditions are related to $PM_{2.5}$ concentrations.
7. **Comparing data** to evaluate the air sensor data against different air quality standards and indices like the AQI.

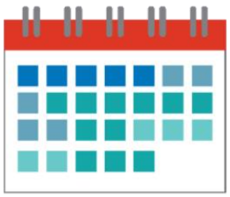
Air sensors produce a large amount of data, so visualizing these data can help you understand what they mean. Many different types of visualizations can be used to explore air sensor data. Figure 3-16 presents some of the most common visualization tools.



Time Series Plots show changes in one or more parameters with time. Useful in comparing trends (pollutants, temperature, multiple sites, etc.).

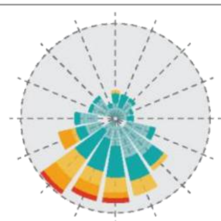


Scatter Plots show the relationship between two parameters. Color coding the dots can indicate a different variable (humidity, temperature, etc.).



Calendar Plots give a big picture look at quality over a month or longer period. Dates can be colored to indicate higher or lower concentrations.

Maps show the spatial patterns of data across a region. Plotting other data such as traffic count or locations of emissions sources can help explain changes in the data.



Wind and Pollution Roses show the frequency of wind direction and can be colored to show pollutant concentrations or wind speed. Useful in showing where higher pollutant concentrations come from.

Figure 3-16. Common Visualization Methods for Air Quality Data

Whether interpreting data in a table or graph, users should ask questions about what they can see in these visual plots. Some questions to ask include:

- Where and when do high (or low) concentrations occur?
- Are there certain characteristics (e.g., weather conditions, emissions patterns, days of the week, season) that lead to high concentrations?
- How do pollutant concentrations change during the day? Are they lower or higher during nighttime, and why?
- What are the prevailing wind directions during a period of interest (e.g., the occurrence of high $PM_{2.5}$ concentrations), and where did the air originate?
- How do measured concentrations compare to concentrations from nearby reference stations?
- How do measured concentrations compare to health indices like the AQI?

3.8.2 Communicating Results

Sensor users may wish to communicate their findings to a variety of different audiences including members of their community, government officials, regulators, industry, or others. The approaches taken (e.g., brief or detailed summary, technical details) and methods used (e.g., social media, presentations, written materials) may need to be tailored to each audience to most effectively communicate information. Communicating the data and results in an open and transparent way can help sensor users build trust in newer and rapidly changing sensor technology. Consider the following elements when seeking to communicate data:

1. **State your purpose or objective**. This information can help you communicate why you conducted the study and why you made some of your decisions. It is crucial to describe how air sensors provided sufficient data quality to meet the project objective(s). Results should be tailored to answer your monitoring question.

2. **Describe the monitoring setup and data**. Providing a clear description of where sensors were located and the data collected allows others to gain confidence in the data and results. Make sure your study files/reports include information about sensor locations, site photographs, QC checks, time stamps, units, formulas for calculated values, etc. Some of this information can be documented in a *data dictionary* which is a description of the parameters collected. It is useful to retain these records for some time beyond the study time frame because it may be necessary to retroactively adjust data as more information regarding sensor performance or data correction becomes available.

3. **Describe the data processing and analysis***.* When communicating data and results, it is recommended that information on the following topics be addressed and clearly documented:

    - Data cleaning and corrections/data adjustments
    - QC checks
    - Data analysis and interpretation, including software/methods used
    - Maintenance and operations
    - Limitations of the data and air sensors

4. **Visualize the data and share the results*.*** There are many ways to visualize data (e.g., graphs, tables, animations). How you chose to display your data may be based on your project objective and/or the audience you are sharing your results with. Some suggestions include:

- **Graphs**: Time series plots that show sensor data compared to regulatory monitor data; time series plots that show how concentrations change over time; maps that show how concentrations differ in space (see Figure 3-16).
- **Tables:** Show numerical sensor data at different locations or at different time to show areas where/when concentrations were elevated.
- **Animations:** Video-like images that show pollutant concentrations as they change in time and/or space.

> **Tip: Know your audience before presenting your results!**
>
> *When presenting results, know your audience. Having knowledge of who is in your audience can help you determine how much information they want and what type of visuals may work best for sharing results. For example, a scientist may want technical details on a project while others may want a big picture summary. Be sure to include the main take-aways and call to action or next steps for your project.*

3.8.3 Take Action

One advantage of air sensors is that allow for measurement of air quality often in real-time in more locations. This local information can empower a variety of decisions, specifically behavioral changes to reduce emission of pollutants and to reduce your exposure to pollutants. Both these actions can improve the air quality and improve your health. Here are some examples of ways to take action based on air sensor data:

- **Adjust your outdoor activities** (e.g., walking, exercising, running errands) biking, gardening,) if sensors measure higher pollution levels. Carry out your activities when pollution levels are lower.
  - Schools choose to have an activity indoors rather than outdoors or move an activity indoors when sensors show that air pollution is high on a given day.
  - Avoid a busy road and use a different route if sensors are measuring higher pollution on a given day.
- **Adjust your indoor activities** if sensors measure higher pollution levels. Consider ways to adjust your habits or to clean the space to reduce pollution levels.
  - Grill outside or open windows to increase ventilation to reduce indoor pollution from cooking.
  - Choose cleaning products with fewer VOCs and fragrances.
  - Reduce smoking and candle, incense or wood (fireplace) burning indoors to eliminate a pollution source.
  - More frequently clean pet hair or dust to reduce indoor $PM_{2.5}$ concentrations.
  - Run a mechanical (e.g., device with a filter) or low-ozone producing electronic air cleaner if an indoor sensor measures elevated pollutant

concentrations. The California Air Resources Board (CARB) provides a list of certified air cleaning devices.
  - Build a DIY air cleaner if a nearby air sensor indicates elevated levels of $PM_{2.5}$ due to wildfire smoke.
- **Look for improvements in air quality after implementing a pollution reduction strategy.**
  - Anti-idling programs at schools may reduce measured concentrations of NO_2 and $PM_{2.5}$ in drop-off and pick-up areas.
  - A vegetative barrier installed along a roadway may reduce the amount of pollution impacting a populated area nearby.
  - Fireplace change out programs or burn bans may reduce PM concentrations.

Ways to use air sensor data to change behavior is an active area of research and is likely to evolve as air sensors become more accurate and deployments more widespread. Air sensor technologies may significantly shape how individuals and communities perceive and respond to information about their air quality. Given the complexity of the science of air pollution and rapidly evolving air sensor technology (e.g., improvements in ease-of-use, data quality, interpretation), how individuals and communities use air sensor data for personal action can depend on many factors, as shown in Figure 3-17.

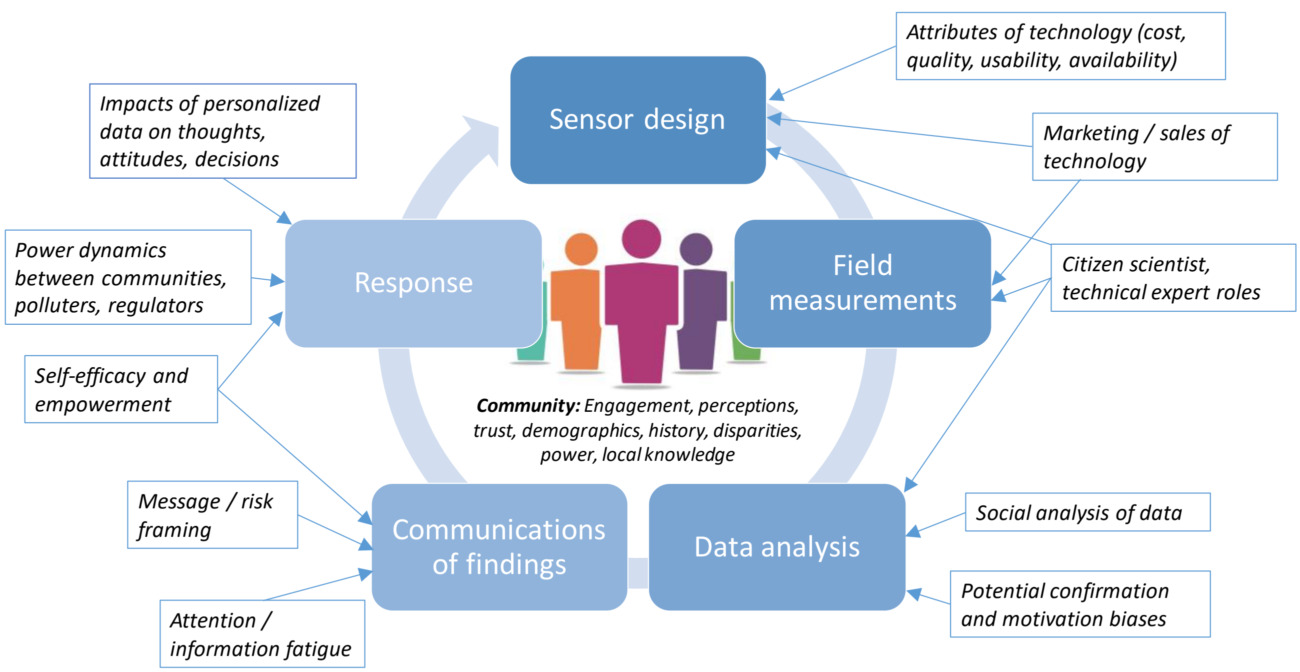


Figure 3-17. Factors that Can Contribute to how Individuals or Communities use Air Sensor Data for Personal Action (Source: Understanding social and behavioral drivers and impacts of air quality sensor use)

- **Personal Strategies to Minimize Effects of Air Pollution on Respiratory Health: Advice for Providers, Patients and the Public,** Carlsten C., S. Salvi, G.W.K. Wong, K.F. Chung. *European Respiratory Journal* 55(6), 2020
  - Paper provides guidance based on findings from published literature to assist health care providers, patients, public health officials, and the public to reduce exposure to indoor and outdoor air pollution
  - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7270362/

- **The AirSensor Open-source R-package and DataViewer Web Application for Interpreting Community Data Collected by Low-cost Sensor Networks**, Feenstra B., A. Collier-Oxandale, V. Papapostolou, D. Cocker, and A. Polidori. *Environmental Modelling & Software* 134, 2020
  - Paper summarizes the development of two software systems to assist in visualizing and understanding air sensor data collected by community networks. *AirSensor* is an open-source R package that allows users to access historical data, add geospatial metadata, and visualize community monitoring data using maps and plots. *DataViewer* is an interactive web application that incorporates the functionality and data plotting functions of *AirSensor* for interpreting and communicating community data collected by low-cost sensor networks
  - https://www.sciencedirect.com/science/article/pii/S1364815220308896

- **AirSensor v1.0: Enhancements to the Open-Source R Package to Enable Deep Understanding of the Long-Term Performance and Reliability of PurpleAir Sensors**, Collier-Oxandale A., B. Feenstra, , V. Papapostolou, and A. Polidori. *Environmental Modelling & Software* 148, 2022
  - Paper describes the enhancements made to the open-source R package AirSensor (version 1.0) and the web application DataViewer (version 1.0.1). to support data access, processing, analysis, and visualization for the PurpleAir PA-II sensor. The paper also demonstrates how the enhancements help track and assess the health of air sensors in real-time and historically
  - https://www.sciencedirect.com/science/article/pii/S136481522100298X

- **Understanding Social and Behavioral Drivers and Impacts of Air Quality Sensor Use,** Hubbell B.J., A. Kaufman, L. Rivers L, K. Schulte, G. Hagler, J. Clougherty, W. Cascio, and D. Costa. *Science of the Total Environment* 621 (2018): 886-894
    - Paper discusses the social science research conducted on air sensor use and identifies: (1) research opportunities between the social and environmental sciences and the entities involved in developing, testing, and deploying air sensor technologies; (2) the challenges associated with sensor data generation, interpretation, and analysis; and (3) collaboration opportunities for communities and organizations to better understand the reasons and approaches for using sensors and how technological innovations may improve the ability to reduce exposures to air pollution
        - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6705391/

- **A Visual Analytics Approach for Station-Based Air Quality Data,** Du, Y., C. Ma, C. Wu, X. Xu, Y. Guo, Y, Zhou, and J. Li. *Sensors* 17(1), 2016
    - Paper proposes a comprehensive visual analysis system (*AirVis*) for air quality analysis that integrates several visual methods, such as map-based views, calendar views, and trends views, to analyze multi-dimensional spatiotemporal air quality data
    - https://www.mdpi.com/1424-8220/17/1/30/htm

- **AtmoVis: Visualization of Air Quality Data,** Powley, B., Master of Science Thesis, Victoria University of Wellington, New Zealand, 2019
    - Document discusses the results from a search of literature regarding systems and methods for visualizing and evaluating air pollution and presents AtmoVis – a web-based system that includes visualizations for site view, line plot, heat calendar, monthly rose, monthly averages, and data comparisons
    - https://homepages.ecs.vuw.ac.nz/~djp/files/MSc_BenPowley_2019.pdf

- **Openair – An R Package for Air Quality Data Analysis,** Carslaw, D.C. and K. Ropkins. *Environmental Modelling & Software* 27-28, 2012
    - *Openair* is an R package used extensively in academia and in the public and private sectors that analyzes air quality data and atmospheric composition data
    - https://davidcarslaw.github.io/openair
    - https://bookdown.org/david_carslaw/openair/

- **U.S. EPA Real Time Geospatial Data Viewer (RETIGO)**
    - REal TIme GeOspatial Data Viewer (RETIGO) is a free, web-based tool that can be used to explore stationary or mobile environmental data that you have collected; nearby public air quality and meteorological data can be added to the display
    - https://www.epa.gov/hesc/real-time-geospatial-data-viewer-retigo

- **U.S. EPA AirData: Air Quality Data Collected at Outdoor Monitoring Stations Across the U.S.**
    - A website providing tools and access to recent and historical air quality information for the U.S., Puerto Rico, and the U.S. Virgin Islands; view data on an interactive mapping application; obtain information about each monitor; and download daily and annual concentration data, AQI data, and speciated particle pollution data (primarily from U.S. EPA's Air Quality System database)
    - https://www.epa.gov/outdoor-air-quality-data

- **Community in Action: A Comprehensive Guidebook on Air Quality Sensors,** South Coast Air Quality Management District (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC), September 2021
    - Guidebook for community organizations that covers planning for monitoring using sensors; sensor deployment, use, and maintenance; and data handling, interpretation, and communication
    - http://www.aqmd.gov/aq-spec/special-projects/star-grant

- **California Air Resources Board (CARB) List of CARB-Certified Air Cleaning Devices**
    - A website providing a table of CARB-certified air cleaning devices, a description of the difference between mechanical and electronic air cleaners, and resources to help you select a safe and effective air cleaner
    - https://ww2.arb.ca.gov/list-carb-certified-air-cleaning-devices

- **U.S. EPA Research on Do-It-Yourself (DIY) Air Cleaners to Reduce Wildfire Smoke Indoors**
    - A website providing on overview of EPA research conducted to evaluate the safety and effectiveness of DIY air cleaners; includes a summary and links to the Underwriters Laboratories (UL) safety report findings, answers to frequently asked questions, and links to helpful resources
    - https://www.epa.gov/air-research/research-diy-air-cleaners-reduce-wildfire-smoke-indoors

Chapter 4

Sensor Performance Guidance

Choosing an air sensor that is most appropriate for an intended application can be challenging. Because air sensor data quality is highly variable, sensor data is compared with data from a reference instrument to describe sensor performance. Reviewing available performance information can help users select a sensor that is appropriate for their intended use.

This chapter provides:

- An overview of sensor performance guidance,
- Information about sensor performance evaluations,
- Approaches used to evaluate sensor performance, and
- Information about how to select sensors based on evaluation reports and other information

4.1 Overview of Sensor Performance

There are many air sensors available to the public and new options continue to become available to meet the growing demand for affordable air monitoring technologies. Choosing an air sensor that best fits your application of interest can be challenging. The quality of sensor data can vary, with some sensors producing reliable and interpretable data and others generating numbers that are not related to pollution concentrations. Because of these differences, it is important to consider how a sensor performs before purchasing a device. **Sensor performance** is a term used to describe how well a sensor works relative to a reference instrument to determine how much confidence we should have in the data produced by a sensor. Having an understanding of the approaches used to determine sensor performance, where to find that information, and how to interpret the information can help users select a sensor that best suits their application.

4.2 Sensor Performance Evaluations

A **sensor performance evaluation** is a test that compares sensor data to reference instrument data (see example setup in Figure 4-1). Reference instruments are used as they provide highly accurate measurements and are the “gold standard”. Sensor performance evaluations are needed because air sensor data quality is highly variable. Sensors and the way their data is processed is constantly changing and improving, which can also impact performance. Sensor performance evaluations can address common concerns of sensors as summarized in Figure 4-2. This information can also help sensor users in the planning phase of a project to select a sensor (see *Section 3.4* and Figure 3-3).

Figure 4-1. Air Sensors on Tripods (in foreground) with Reference Instruments (in the background) to Evaluate Sensor Performance. Photo Credit: South Coast Air Quality Monitoring District (AQMD)

Ability to measure pollutant of interest	• Does the sensor measure the pollutant of interest accurately and reliably within the expected concentration range of the application?
Performance under different environmental conditions	• How do factors such as relative humidity, temperature, and different pollutant concentrations and types impact sensor measurements?
Ability to measure target pollutant in a pollutant mixture	• Will the sensor measure the target pollutant in a mixture of other pollutants?
Performance over time	• How does the sensor response change over time? • When do the sensor readings become inaccurate or unreliable?
Performance out-of-the-box	• How does the sensor perform out-of-the-box? • Are corrections or adjustments needed to provide more accurate data?
Useful Lifetime	• Does how long a sensor runs change how the sensor responds? • Is the lifetime of the sensor impacted by concentration range or whether the sensor is in use or not?

Figure 4-2. Common Concerns Related to Sensor Performance

A number of sensor performance evaluations have been conducted and results are publicly available from many testing organizations, both within the U.S. and internationally, including:

- U.S. EPA Office of Research and Development (ORD)
- South Coast Air Quality Management District (South Coast AQMD) Air Quality Sensor Performance Evaluation Center (AQ-SPEC)
- European Commission Joint Research Centre (JRC)
- Airparif AIRLABS Microsensors Challenge
- Academic researchers
- Sensor manufacturers

We expect that additional evaluation centers, laboratories, or organizations may launch in the coming years.

Sensor users should keep in mind that not all sensors, including do-it-yourself (DIY) sensors, have performance evaluations. For evaluations that are available, perspective users should check whether the test conditions were similar to their intended study area or whether changes have been made to the product hardware or firmware since the evaluation was conducted. Additionally, while a sensor may have a performance evaluation, it is important to understand if the evaluation is unbiased and objective. In other words, did the organization that conducted the evaluation do so in a fair and impartial manner.

Although testing organizations, like those previously mentioned, evaluate sensors in different locations and can give users an idea of how a sensor is expected to perform, there might be a need to do an evaluation on your own. If this is not feasible due to resources (e.g., funding, equipment, expertise) or other reasons, you may consider doing the following:

- Ask a testing organization if they have already conducted a sensor evaluation for a device you are interested in. Sometimes evaluations have been conducted but the results have not been shared yet publicly.

- Ask a testing organization if they are planning to evaluate a sensor you are interested in using or if they might be willing to conduct an evaluation.

Sensor users should remember to check and evaluate a sensor's performance within the study area ideally before, during, and after a study if possible. This check is referred to as **collocation** (*see Section 3.6*) and is a necessary part of any sensor project.

What is the Difference Between a Sensor Performance Evaluation and Collocation?

Sensor performance evaluations provide information about how well a sensor performs relative to a reference instrument.

A performance evaluation, at the core, is a collocation. However, it is a collocation conducted by an objective testing organization for the specific purpose of informing others about how well the sensor agrees with reference instruments under the test conditions. Manufacturers may use the results to improve their sensor products. Potential sensor users may use the results to decide what sensor(s) to buy for a project.

It is a best practice to collocate air sensors with reference instruments after purchase, as discussed in Section 3.6, to check their performance under outdoor conditions in the desired monitoring location.

Resources for More Information

- **U.S. EPA Air Sensor Performance Evaluations**
  - Collection of results for field and laboratory evaluations of air sensors conducted by U.S. EPA Office of Research and Development
  - https://www.epa.gov/air-sensor-toolbox/evaluation-emerging-air-sensor-performance

- **South Coast Air Quality Management District (South Coast AQMD) Air Quality Sensor Performance Evaluation Center (AQ-SPEC)**
  - Field and laboratory evaluations of commercially available air sensors conducted by AQ-SPEC
  - http://www.aqmd.gov/aq-spec

- **European Commission Joint Research Centre (JRC)**
  - Results for field and laboratory evaluations of air sensors primary in the form of scientific journal articles and reports
  - https://publications.jrc.ec.europa.eu/repository/
- **AirParif AIRLABS Microsensors Challenge**
  - Results from an international challenge that promotes innovation and helps inform users on the performance of air sensors in different applications
  - http://www.airlab.solutions/en/projects/microsensor-challenge

4.3 Approaches Used to Evaluate Sensor Performance

There are two main approaches for evaluating air sensor performance**: field evaluations** and **laboratory evaluations**. Table 4-1 briefly summarizes these approaches and their purpose in more detail.

Table 4-1. Common Approaches for Evaluating Air Sensor Performance

Evaluation Approach	Description	Purpose
Field	Sensors evaluated in the field at an ambient (outdoor) fixed site	• Gives information on how a sensor performs in real-world, outdoor conditions • Gives users information on how they might expect a sensor to perform in similar outdoor conditions
Laboratory	Sensors evaluated in a controlled laboratory setting	• Allows us to study a range of conditions that may be more difficult to come across outdoors • Allows us to better understand certain performance parameters that are difficult to test outdoors

Field evaluations typically involve collocating one or more sensors side-by-side with a reference instrument(s) for an extended period of time (e.g., days, months, years) outdoors. In field evaluations, sensors experience typical changes in pollutant concentrations and daily swings in temperature (T) and relative humidity (RH). Sensors may also experience typical weather conditions (e.g., rain, fog, snow, high winds) that may impact how a sensor performs. When operating outdoors, sensors will also experience different pollutant mixtures which can test how well a sensor can detect the target pollutant. One downside of a field evaluation is that outdoor conditions cannot be controlled. This means that it will be impossible to understand how a sensor will perform under conditions that are not present. For example, an evaluation during the summer will not tell you how a sensor may perform in colder temperatures. Additionally, it can be difficult to figure out if changes in the pollutant concentration level, pollutant mixture, or environmental conditions are affecting sensor performance, especially when these conditions change at the same time.

Laboratory evaluations are typically short-term evaluations (e.g., hours) conducted in an environmentally controlled chamber. One or more sensors and the inlet(s) of a reference instrument(s) are placed in the chamber and exposed to different test conditions (e.g., high or low temperatures, high or low humidity, target and interferent pollutant concentrations and types) and the measurements are compared. Laboratory evaluations are useful as they can provide information on how sensors perform in specific environmental conditions that may commonly or rarely happen outdoors. However, an environmental chamber can only mimic specific real-world, outdoor environmental conditions. For example, a laboratory cannot simulate the size and chemical composition of particles in the outdoor air nor conditions like fog. While laboratory evaluations are extremely useful, they are more expensive because they require complex equipment and skilled staff to run the tests. In addition, the results represent sensor performance for a specific set of conditions which may or may not occur outdoors.

As discussed, there are pros and cons associated with each sensor performance evaluation approach. This is often why both approaches are recommended since they complement each other, and the information collected overall is useful to better understand sensor performance. Based on the purpose for monitoring, sensor users will need to decide what performance evaluation approaches can best inform what sensors are selected for a project. This decision may depend on the availability of resources (e.g., funding, knowledge, expertise) and access to field sites and/or laboratory testing facilities. Ideally, at a minimum, field testing in the location where sensors will be used is recommended.

4.3.1 U.S. EPA Recommendations on Evaluating Sensor Performance

What is the Difference Between EPA's Recommendations for Evaluating Sensors and Sensor Standards/Certification Programs?

U.S. EPA's recommended protocols are entirely voluntary and testing results that meet some or all of the targets does not constitute certification. Further, U.S. EPA does not endorse or recommend any specific product.

Setting **sensor standards** is a voluntary process where technology testing methods are agreed upon by authorities, manufacturers, customers, and others invested in the performance of the technology.

Certification is a process where an organization carries out an agreed upon test methods set by standards to make sure tests are conducted in the same way every time. The certification process often results in a certificate or specific label.

Recognizing the need for a consistent approach for evaluating air sensor performance, the U.S. EPA published reports (herein called 'Targets Reports') that provide recommendations on how to evaluate air sensors that measure criteria pollutants. The U.S. EPA's recommendations provide a standardized, objective, and streamlined approach for evaluating air sensor performance. The U.S. EPA based its recommendations on the current state-of-the-science, literature reviews, findings from other sensor evaluation organizations, sensor standards/certification programs (both existing and in development) by other organizations, and the U.S. EPA expertise in sensor evaluation. The Targets Reports include the following:

- **Testing protocols** – step-by-step instructions for setting up instruments, testing instruments, and collecting data
- **Performance metrics** – parameters used to describe data quality and details on how to calculate them
- **Target values** – recommended values that provide a benchmark to understand sensor performance

The evaluations include both field testing (called **base testing**) and laboratory testing (called **enhanced testing**). At minimum, base testing is recommended. The testing protocols are specifically designed for sensors used in ambient, outdoor, fixed site environments for non-regulatory supplemental and informational monitoring (NSIM) applications (see Section 1.1, Table 1-1). As a brief summary, NSIM categories and specific examples of applications include:

- **Spatiotemporal Variability** – daily trends, gradient studies, air quality forecasting, participatory science, education
- **Comparison** – hotspot detection, data fusion, emergency response, supplemental monitoring
- **Long-term Trend** – Long-term changes, epidemiological studies, model verification

As part of the Targets Reports, the base and enhanced testing protocols have a reporting template to encourage testers to present evaluation results using a similar format. Information on how to interpret these reports is provided in Appendix E. Additionally, an EPA-developed Python code library called *sensortoolkit* is available to help testing organizations calculate the performance metrics and generate the evaluation report using the reporting template. Links to the reports, reporting templates, and Python code library are all available from EPA's Air Sensor Toolbox webpage.

The intended audience for U.S. EPA's Targets Reports includes testing organizations (e.g., routine evaluation organizations, sensor manufacturers); although, sensor users may also choose to perform the testing protocols. Conducting the protocols is entirely voluntary. Additionally, the results from the evaluations do not constitute certification or endorsement by the U.S. EPA. The testing results are meant to inform sensor users.

4.3.2 Guidance from other Organizations on Evaluating Sensor Performance

A number of organizations have developed or are in the process of developing guidance on conducting sensor performance evaluations, sensor targets/standards, or sensor certification programs. Examples of these organizations include:

- **ASTM International** – developing standards of practice and test methods for field and laboratory evaluations of ambient and indoor air sensors measuring common air pollutants.
- **European Union/European Committee for Standardization (EU/CEN)** – developing field and laboratory certification procedures for multiple tiers of sensor applications.
- **China Ministry of Ecology and Environment (MEE)** – developed field and laboratory test procedures and performance standards for air sensors.

Resources for More Information

- **U.S. EPA Performance Testing Protocols, Metrics, and Target Values for Air Sensors – Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications**
    - Reports that provide recommended testing protocols (field and laboratory), performance metrics (parameters used to describe sensor data quality), and target levels to evaluate air sensors that measure criteria air pollutants
    - https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

- **ASTM WK64899 "New Practice for Performance Evaluation of Ambient Air Quality Sensors and Other Sensor-Based Instruments"**
    - Provides information on a practice for evaluating the performance of air quality sensors in ambient air
    - https://www.astm.org/workitem-wk64899

- **EU/CEN/TC 264/WG 42 "Air quality – Performance evaluation of air quality sensor systems – Part 1: Gaseous pollutants in ambient air"**
    - Outlines testing procedures and requirement for classifying performance of air quality sensors for the monitoring of gaseous pollutants
    - https://www.en-standard.eu/pd-cen-ts-17660-1-2021-air-quality-performance-evaluation-of-air-quality-sensor-systems-gaseous-pollutants-in-ambient-air/

- **Air Quality Sensor Performance Evaluation Center (AQ-SPEC) of the South Coast Air Quality Management District (South Coast AQMD) Website**
    - Website for the AQ-SPEC program which describes how field and laboratory tests are conducted
    - Field Evaluation Protocol and Reports: http://www.aqmd.gov/aq-spec/evaluations/field
    - Laboratory Evaluation Protocol and Reports: http://www.aqmd.gov/aq-spec/evaluations/laboratory

4.4 How to Select Sensors Based on Evaluation Reports or Information

Reviewing sensor performance evaluation reports and related information can help you select an appropriate sensor for your project. Some questions to ask when reviewing an evaluation report and determining whether a sensor would be suitable for your monitoring project application include:

- **Trends:** How well do the changes in sensor measurements mimic the change in pollutant concentrations that are measured by the reference instrument?
- **Precision:** How consistent are the concentration measurements obtained by sensors of the same make, model, and firmware version that are operated under the same field conditions?

- **Bias:** How closely do the sensor measurements agree with measurements made by a collocated reference instrument?
- **Concentration Range:** Does the operating range of the sensor cover the range of pollutant concentrations expected at the desired monitoring location?
- **Meteorology:** Is the sensor response affected by meteorological conditions (e.g., RH, T)?
- **Specificity:** Does the sensor measure the target pollutant? Are the sensor measurements affected by an interferent(s)?
- **Drift:** Is the sensor response to pollutant concentrations stable over time?

What are the Definitions of Precision, Bias, and Drift?

Bias: The systematic or persistent disagreement between concentration reported by the sensor and reference instrument.

Precision: The variation around the mean (average) of a set of measurements obtained at the same time from two or more sensors of the same type collocated under the same environmental conditions.

Drift: A change in the response or concentration reported by a sensor when challenged by the same pollutant concentration over an operating timeframe.

Going over the objectives of your project (see Section 3.2) and your plan for obtaining measurements (see Section 3.3), will help you decide on which information is most important to consider when reviewing performance evaluation results. Let's consider two examples:

- **Example #1: You would like to setup a network of sensors for a long-term deployment in a community to supplement an existing regulatory monitoring network**. For this case, you are likely most interested in a **quantitative measurement** of pollutant concentrations. Therefore, you would be most concerned with a sensor's precision, bias, and response to meteorology (i.e., T and RH). The sensors should provide an acceptable degree of agreement between the network of sensors (precision) and between the sensors and reference instrument measurements (bias) to allow you to confidently compare sensor data to the regulatory monitoring network and to air quality and health standards. Because the sensors need to provide reasonable measurements under all meteorological

What is the Difference Between Quantitative and Qualitative Measurements?

Quantitative measurements can be expressed using numbers. For example, a pollutant concentration expressed in parts per billion (ppb).

Qualitative measurements are descriptive, based on concepts, and often expressed in words. For example, pollutant concentrations described as "higher" or "lower".

conditions expected over the deployment period, you may be interested in knowing if the sensor was tested under similar meteorological conditions and whether bias changes as RH changes.

- **Example #2: You would like to use one sensor to measure an air pollutant in your backyard to determine when air quality is best for outdoor activities**. In this case, you are likely interested in a **qualitative measurement**. In other words, a sensor that reliably provides information about the relative difference between high and low pollutant concentrations (trends) might be sufficient.

Figure 4-3 provides a flow chart with considerations on how to select sensors based on their performance. As mentioned in Section 4.1, many organizations and manufacturers themselves conduct sensor performance evaluations. These can normally be found on the organization or manufacturers' webpages or in scientific publications (e.g., presentations, journal articles).

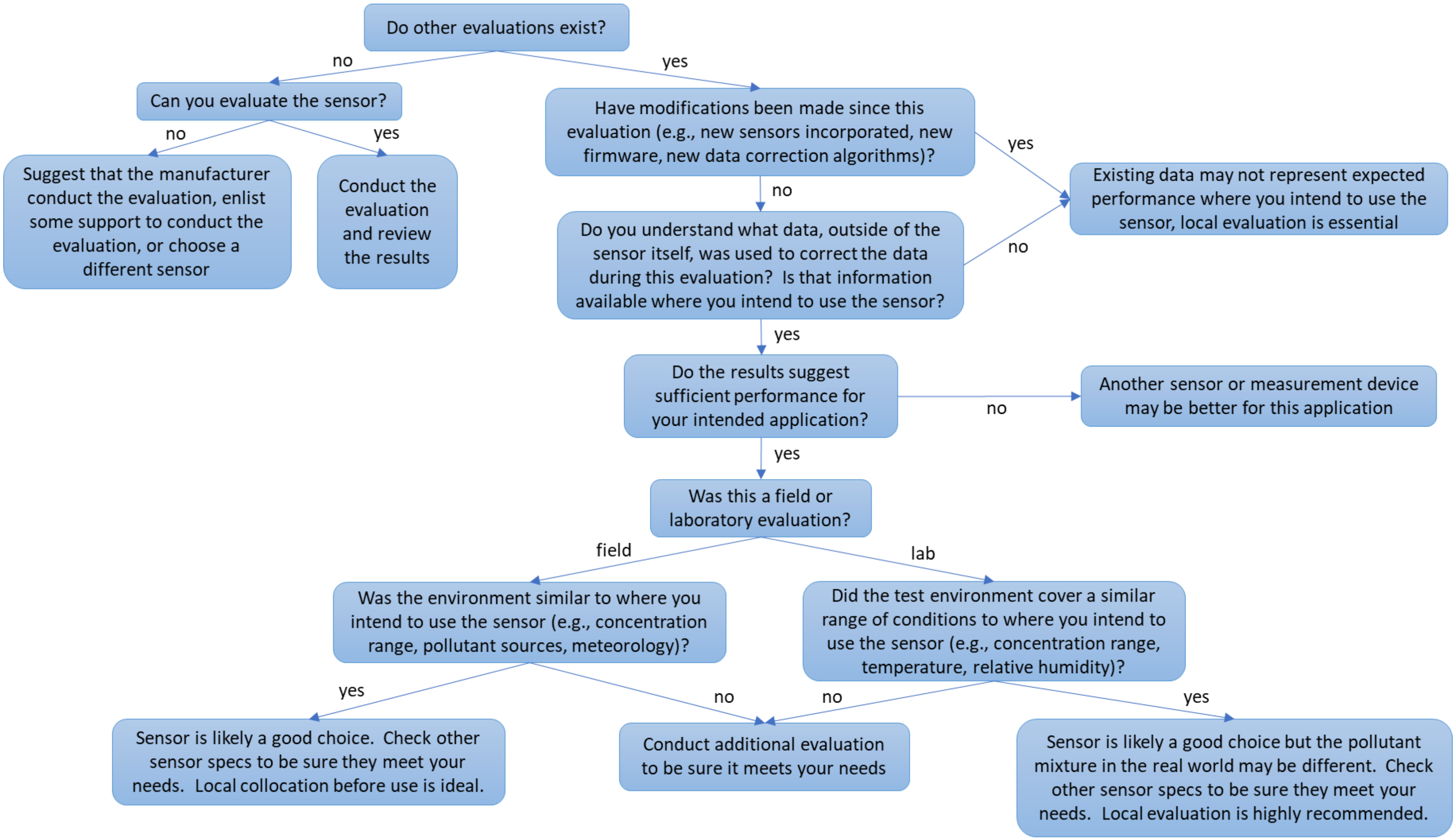


Figure 4-3. Flow Chart for Considering an Air Sensor Based on Performance

As you review sensor performance evaluations across different testing organizations, look for as much information as possible to understand the performance of a device. Remember that the level of detail and transparency can be different from one evaluation to the next. Below are some important notes to keep in mind and questions to ask about the evaluations to help you better understand the testing and results:

1. **Evaluation protocols/procedures may be similar but not identical.** Those conducting the tests may have different protocols, laboratory test pollutant concentrations, or report different performance metrics. Graphs or plots describing performance may look similar but may be generated or plotted differently. The terminology used and how the performance metric(s) is calcuated may vary. For example, precision might be calculated as either the standard deviation, relative standard deviation, or relative percent difference. Evaluations may use different types of reference instruments. Use of a FRM/FEM instrument(s) will provide greater confidence in actual pollutant concentrations than the use of another mid to lower-cost sensor. There can be some differences in the results depending on which FRM/FEM is used.
    - Were both field and laboratory evaluations conducted?
    - Was an FRM/FEM instrument used? Which one?
    - Do you understand the performance metrics and how they were calculated?
2. **Locations are not widespread.** Generally, evaluations are conducted at a limited number of locations which may or may not be similar to the environment where you want to use the sensor. The evaluation results may not represent how a sensor performs in the environment you will use them in if that environment is very different (e.g., different pollutant concentration, composition, or sources).
    - Where was the test conducted?
3. **Environmental conditions are limited.** Consider whether the sensor was tested in an environment similar to where you will be using the sensor. Generally, sensor evaluations are conducted outdoors where T, RH, and other weather conditions vary. These conditions may not be similar to the environment where you want to place the sensor(s). Similarly, evaluation results may not represent sensor performance in the environment you will use them in if that environment is very different (e.g., T and RH often outside of the tested range).

Tip: Find performance evaluations that match the conditions you expect in your monitoring study

To the extent possible, find performance evaluations for the type of sensor and deployment conditions (e.g., pollutant concentration, RH, T) anticipated in your monitoring study.

- Was the test conducted in an environment similar to where you will be using the sensor?

4. **Sensor performance is variable.** It is a standard practice to test 3 or more identical sensors at the same time because it provides information on the variation in performance that can occur among identical sensors. Performance can vary based on the make, model, and firmware version of the device and even among devices of the same type. Past evaluation efforts have shown that two sensor packages that use the same internal component can perform differently. These differences can be a result of how the components are arranged, how they sample the air, or due to a build up of heat inside of the sensor housing. Additionally, manufacturers may use a mathematical equation or model to convert the output from the sensor into a pollutant concentration. Differences in data processing can change sensor performance. Firmware changes can also impact sensor performance.
    - Did all sensors tested perform similarly?
    - Did the sensors tested have the same make, model, configuration, and firmware as the sensors you intend to use?
5. **Evaluations are conducted for a finite amount of time.** Typically, sensor performance evaluations are conducted for 30 days or more as it allows for more variation in pollutant concentrations and environmental conditions. Shorter evaluations may not be able to capture these variations. Longer evaluations may be needed to understand how sensor performance changes over time and sensor lifetime. Unexpected events such as power outages, equipment failure or damage, inclement or severe weather (e.g., thunderstorms, hurricanes), or pollution episodes (e.g., fireworks, dust storms, volcanic eruption) can influence evaluation results or cause missing data.
    - How long was the evaluation (e.g., 7 days, 30 days, 1 year)?
6. Were there any difficulties or anomalies encountered during the test that might influence the results? **The evaluation may not represent your intended application.** A sensor may have been tested near a source (e.g., roadway, industry) where pollutant concentrations are much higher than where you intend to use the sensor.
    - Was the sensor performance evaluation conducted in an enviroment similar to your application of interest?

- **U.S. EPA Performance Testing Protocols, Metrics, and Target Values for Air Sensors – Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications**
    - Reports that provide recommended testing protocols (field and laboratory), performance metrics (parameters used to describe sensor data quality), and target levels to evaluate air sensors that measure criteria air pollutants
    - Appendices of the Targets Reports provide standardized reporting templates
    - https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

- **U.S.-EPA developed *sensortoolkit* python code library**
    - Code library for evaluating air sensor data collocated with reference instruments; code can be used to calculate performance metrics
    - GitHub: https://github.com/USEPA/sensortoolkit
    - PyPI: https://pypi.org/project/sensortoolkit/

- **U.S.-EPA $PM_{2.5}$ Continuous FEM Monitor Comparability Assessments**
    - Tool providing a one-page technical report that assesses the comparability of a $PM_{2.5}$ continuous FEM monitors when collocated with an FRM sampler
    - https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments

- **Air Quality Sensor Performance Evaluation Center (AQ-SPEC) of the South Coast Air Quality Management District (South Coast AQMD) Website**
    - Website for the AQ-SPEC program which describes how field and laboratory tests are conducted
    - Field Evaluation Protocol and Reports: http://www.aqmd.gov/aq-spec/evaluations/field
    - Laboratory Evaluation Protocol and Reports: http://www.aqmd.gov/aq-spec/evaluations/laboratory

Appendix A: Resources

A.1 Introduction to Air Sensors

- **U.S. EPA's Air Sensor Toolbox**
  - Information and resources for topics related to air sensors; includes links to other organizations and resources that sensor users may find helpful
  - https://www.epa.gov/air-sensor-toolbox

A.2 Air Quality 101

A.2.1 Outdoor Air Quality and Air Pollution

- **U.S. EPA Air Quality Planning and Standards Website**
  - Provides additional information regarding air quality and pollutants
  - https://www3.epa.gov/airquality/

- **U.S. EPA National Air Quality – Status and Trends of Key Air Pollutants Website**
  - Provides air quality trends, reports, and summaries for criteria air pollutants
  - https://www.epa.gov/air-trends

- **U.S. EPA AirNow Website**
  - Provides a variety of resources on air quality including air quality information at local, state, national, and world views, air quality and health, maps and data, educational resources, and more
  - https://www.airnow.gov/

- **Wildfire Smoke: A Guide for Public Health Officials,** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-452/R-19-901, August 2019
  - Document provides guidance to state, tribal, and local public health officials and other interested groups (e.g., health professionals, air quality officials, public) in preparing for wildfire smoke events and in communicating health risks and taking measures to protect the public during smoke events
  - https://www.airnow.gov/sites/default/files/2021-05/wildfire-smoke-guide-revised-2019.pdf

- **U.S. EPA Mobile Source Pollution and Related Health Effects Website**
    - Overviews mobile sources of air pollution, summarizes health effects associated with exposure to mobile source emissions, provides data and modeling resources, and information on programs to reduce mobile source pollution
    - https://www.epa.gov/mobile-source-pollution

- **U.S. EPA Near-Roadway and Other Near-Source Pollution Website**
    - Overview of research on near-roadway pollution from cars, trucks, and other mobile sources and frequently asked questions about near-roadway air pollution and health effects
    - https://www.epa.gov/air-research/research-near-roadway-and-other-near-source-air-pollution

- **Near-Roadway Air Pollution and Health: Frequently Asked Questions,** U.S. Environmental Protection Agency, Office of Transportation and Air Quality, EPA-420-F-14-044, August 2014
    - Document provides U.S. EPA's responses to frequently asked questions received from the public regarding exposure to near-roadway air pollution
    - https://nepis.epa.gov/Exe/ZyPDF.cgi/P100NFFD.PDF?Dockey=P100NFFD.PDF

- **Report to Congress on Black Carbon,** U.S. Environmental Protection Agency, EPA-450/R-12-001, March 2012
    - Document summarizes available scientific information on the current and future impacts of black carbon (BC) and evaluates the effectiveness of available BC mitigation approaches and technologies
    - https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100EIJZ.txt

- **U.S. EPA Integrated Science Assessments (ISAs) for Criteria Air Pollutants Website**
    - Reports that summarize scientific information that is the foundation for reviewing the NAAQS for criteria pollutants; ISAs are an important resource for state and local health agencies, other federal agencies, and international health organizations
    - https://www.epa.gov/isa

A.2.2 Health And Environmental Effects of Air Pollution

- **U.S. EPA Criteria Air Pollutants Website**
  - Provides detailed information on the six criteria pollutants including basic information, health and environmental effects, technical documents, setting and reviewing the standards, implementing the standards, and current air quality designations
  - https://www.epa.gov/criteria-air-pollutants

- **Health Effects of Ozone (O_3) Pollution Website**
  - Provides detailed information on health effects of breathing air containing O_3
  - https://www.epa.gov/ground-level-ozone-pollution/health-effects-ozone-pollution

- **Health and Environmental Effects of Particulate Matter (PM) Website**
  - Provides detailed information on health and environmental effects of PM
  - https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

- **Basic Information about Nitrogen Dioxide (NO_2) Website**
  - Provides basic information on NO_2 including health and environmental effects
  - https://www.epa.gov/no2-pollution/basic-information-about-no2#Effects

- **Basic Information about Sulfur Dioxide (SO_2) Website**
  - Provides basic information on SO_2 including health and environmental effects
  - https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects

- **Basic Information about Carbon Monoxide (CO) Outdoor Air Pollution Website**
  - Provides basic information on CO including health and environmental effects
  - https://www.epa.gov/co-pollution/basic-information-about-carbon-monoxide-co-outdoor-air-pollution#Effects

- **Basic Information about Lead (Pb) Air Pollution Website**
  - Provides basic information on Pb including health and environmental effects
  - https://www.epa.gov/co-pollution/basic-information-about-carbon-monoxide-co-outdoor-air-pollution#Effects

- **Report on the Environment – Volatile Organic Compounds (VOCs) Emissions Website**
  - Provides detailed information on sources, health and environmental effects, and emissions estimates of VOCs
  - https://cfpub.epa.gov/roe/indicator.cfm?i=23#1

- **Definition of VOC Website**
    - Provides a detailed information on the definition of VOCs as outlined in air pollution regulations
    - https://www.epa.gov/air-emissions-inventories/what-definition-voc

- **Health Effects of Exposures to Mercury Website**
    - Provides detailed information on health effects of exposure to mercury
    - https://www.epa.gov/mercury/health-effects-exposures-mercury

- **Integrated Risk Information System (IRIS) Methylmercury (MeHg) Summary Website**
    - Provides health assessment information on MeHg based on review of toxicity data
    - https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=73

- **Agency for Toxic Substances and Disease Registry (ATSDR) Public Health Statement for Benzene Website**
    - Provides information about benzene and effects of exposure to it
    - https://wwwn.cdc.gov/TSP/PHS/PHS.aspx?phsid=37&toxid=14

- **Integrated Risk Information System (IRIS) Benzene Summary Website**
    - Provides health assessment information on benzene based on review of toxicity data
    - https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=276

- **Global Methane Initiative (GMI) Website**
    - Provides information on GMI, description of methane and mitigation approaches, methane sites around the globe, and more
    - https://www.epa.gov/gmi

- **Report to Congress on Black Carbon**, U.S. Environmental Protection Agency, EPA-450/R-12-001, March 2012
    - Report provides summary on black carbon, health and environmental effects, emissions, mitigation overview, and more
    - https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100EIJZ.txt

- **Integrated Science Assessment (ISA) for Particulate Matter**, U.S. Environmental Protection Agency, EPA/600/R-19/188, December 2019
    - ISA provides detailed information on particulate matter including sources, ambient levels, health and environmental effects, and more
    - https://www.epa.gov/isa/integrated-science-assessment-isa-particulate-matter

- **Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects**, HEI Panel on the Health Effects of Traffic-Related Air Pollution, HEI Special Report 17, Health Effects Institute (HEI), January 2010
    - Report provides a summary and synthesis of information on air pollution from traffic and its health effects
    - https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health

A.2.3 Air Pollution Monitoring

- **U.S. EPA Ambient Monitoring Technology Information Center (AMTIC) Website**
    - Contains technical information regarding ambient air monitoring programs, including the networks of state and local air monitoring stations (SLAMS), monitoring methods, and QA/QC procedures
    - https://www.epa.gov/amtic

- **U.S. EPA Ambient Air Monitoring Website**
    - Overviews the reasons for why monitoring ambient air quality is important and provides links to U.S. EPA's AMTIC, Air Quality System (AQS), Air Data, AirNow, and AirNow International websites
    - https://www.epa.gov/air-quality-management-process/managing-air-quality-ambient-air-monitoring

- **Overview of the Clean Air Act (CAA) Website**
    - Provides an in-depth overview of the CAA including history and requirements, role of science and technology, role of state, local, tribal and federal government, and more
    - https://www.epa.gov/clean-air-act-overview

- **Videos on Sources of Air Quality Information and Air Sensor Measurements, Data Quality, and Interpretation**
    - Educational videos, in both English and Spanish, that can be used to learn how U.S. EPA collects and uses air quality data, how air quality health risks are communicated, and how to interpret data collected using air sensors
    - https://www.epa.gov/air-sensor-toolbox/videos-air-sensor-measurements-data-quality-and-interpretation

- **Understanding Air Quality and Monitoring Video**, South Coast Air Quality Management District (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC), September 2021

- Educational video providing background on air quality, criteria pollutants, pollutant sources and health effects, air quality monitoring technologies, and the role of air sensors
- https://www.youtube.com/watch?v=2r0XxQm50lE

- **California Air Resources Board (CARB) Outline of Measurement Technologies**
  - Online resource that discusses air monitoring applications, applicable measurement technologies, and their relative availability and cost developed by CARB to support community air monitoring conducted under California Assembly Bill 617
  - https://ww2.arb.ca.gov/capp-resource-center/community-air-monitoring/outline-of-measurement-technologies

- **Hazardous Air Pollutants (HAPs) Website**
  - Provides detailed information on HAPs including the list of HAPs, health an environmental effects, sources and exposures, data, and more
  - https://www.epa.gov/haps

- **Regional Haze Program Website**
  - Provides information on the Regional Haze Rule and Program, list of the national parks and wilderness areas covered by the program, and more
  - https://www.epa.gov/visibility/regional-haze-program

A.2.4 Air Quality Standards and Indices

- **WHO National Air Quality Standards Tool**
  - An interactive tool providing an international map of current national air quality standards for criteria pollutants for various averaging times
  - https://www.who.int/tools/air-quality-standards

- **Air Quality in Europe 2021**
  - An annual assessment of recent air quality trends at both European and national levels
  - https://www.eea.europa.eu//publications/air-quality-in-europe-2021

- **Air Quality System Data Dictionary**
  - The AQS Data Dictionary describes the fields typically encountered by AQS users and are listed in alphabetical order; field definitions and calculation algorithms are provided as appropriate
  - https://aqs.epa.gov/aqsweb/documents/AQS_Data_Dictionary.html

- **U.S. EPA National Ambient Air Quality Standards (NAAQS) Table**
    - A webpage detailing the NAAQS for six criteria pollutants which includes details from Table 2-4 but is a resource that will be updated if the standards change
    - https://www.epa.gov/criteria-air-pollutants/naaqs-table

- **The National Institute for Occupational Safety and Health (NIOSH)**
    - The Occupational Safety and Health Act of 1970 established NIOSH as a research agency focused on the study of worker safety and health, and empowering employers and workers to create safe and healthy workplaces
    - https://www.cdc.gov/niosh/index.htm

- **Center for Disease Control and Prevention (CDC) National Environmental Public Health Tracking – Air Quality**
    - CDC works closely with the U.S. Environmental Protection Agency, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Association (NOAA), and the National Weather Service to provide air quality data on the Tracking Network and to better understand how air pollution affects our health
    - https://www.cdc.gov/nceh/tracking/topics/AirQuality.htm

- **Greenbook: Nonattainment Areas for Criteria Pollutants**
    - The EPA Green Book provides detailed information about area National Ambient Air Quality Standards (NAAQS) designations, classifications and nonattainment status
    - https://www.epa.gov/green-book

A.2.5 The U.S. Air Quality Index (AQI)

- **AirNow Air Quality Index (AQI) Website**
    - Provides information on AQI basics, air pollutants, action days, and other resources
    - https://www.airnow.gov/aqi/

- **Technical Assistance Document for Reporting of Daily Air Quality – the Air Quality Index (AQI),** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA 454/B-18-007, September 2018
    - Document provides guidance to aid local agencies in calculating and reporting the AQI as required in the Code of Federal Regulations (CFR)
    - https://www.airnow.gov/publications/air-quality-index/technical-assistance-document-for-reporting-the-daily-aqi/

- **AirNow AQI Calculator**
    - Online tool that converts user-specified AQI values into an equivalent concentration or converts concentration into AQI values. The tool also provides the corresponding AQI Category (e.g., good, moderate), health effects, and cautionary statements
    - https://www.airnow.gov/aqi/aqi-calculator/

- **AirNow – Using the Air Quality Index Website**
    - Provides an overview of the AQI, AQI forecasts, and the NowCast AQI and how to use these tools to assess local air quality and plan for outdoor activities; links on the page provide technical information about NowCast algorithms and leads to a github code library for calculating the NowCast for O_3
    - https://www.airnow.gov/aqi/aqi-basics/using-air-quality-index/

- **Air Quality Index: A Guide to Air Quality and Your Health,** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-456/F-14-002, February 2014
    - Booklet that discusses the importance of air quality and provides an overview of the AQI; health effects of exposure to ozone (O_3), particulate matter (PM), carbon monoxide (CO), and sulfur dioxide (SO_2); and suggested actions to reduce exposure to unhealthy air for each AQI Category
    - https://www.airnow.gov/sites/default/files/2018-04/aqi_brochure_02_14_0.pdf

- **Modified Air Quality Index, Improving Accessibility for People with Color Vision Deficiencies,** South Coast Air Quality Management District (South Coast AQMD), May 2022
    - Press release sharing South Coast AQMD's work to develop a modified version of the AQI that accommodates individuals with color vision deficiencies while still being similar to the traditional AQI color scale; the scale was tested against eight common color impairments and remains distinguishable in grayscale
    - http://www.aqmd.gov/docs/default-source/news-archive/2022/south-coast-aqmd-modified-AQI-05022022

- **Air Quality Guide for Nitrogen Dioxide (NO_2),** U.S. Environmental Protection Agency, Office of Air and Radiation, EPA-456/F-11-003, February 2011
    - Booklet that overviews actions to reduce exposure NO_2 near roadways for each AQI category, provides an overview of NO_2 sources and health effects, and provides tips for reducing NO_2 emissions
    - https://www.airnow.gov/sites/default/files/2018-06/no2.pdf

- **Air Quality Guide for Ozone (O_3),** U.S. Environmental Protection Agency, Office of Air and Radiation, EPA-456/F-15-006, August 2015
  - Booklet that overviews actions to reduce exposure to O_3 for each AQI category, provides an overview of O_3 sources and health effects, and provides tips for reducing pollution from O_3
  - https://www.airnow.gov/sites/default/files/2021-03/air-quality-guide_ozone_2015.pdf

- **Air Quality Guide for Particle Pollution,** U.S. Environmental Protection Agency, Office of Air and Radiation, EPA-456/F-15-005, August 2015
  - Booklet overviews the actions to reduce exposure to particle pollution for each AQI category, provides an overview of pollution sources, and overviews health effects and tips for reducing particle pollution
  - https://www.airnow.gov/sites/default/files/2021-03/air-quality-guide_pm_2015.pdf

A.3 Monitoring Using Air Sensors

A.3.1 Question: Determining a Purpose For Monitoring

- **Handbook for Citizen Science Quality Assurance and Documentation**, U.S. Environmental Protection Agency, EPA 206-B-18-001, March 2019
  - Handbook that covers common expectations for quality assurance and documentation and best management practices for organizations that train and use volunteers in the collection of environmental data
  - https://www.epa.gov/sites/default/files/2019-03/documents/508_csqapphandbook_3_5_19_mmedits.pdf

- **Guidebook for Developing a Community Air Monitoring Network: Steps, Lessons, and Recommendations from the Imperial County Community Air Monitoring Project**, Tracking California, October 2018
  - Outlines the process and considerations for creating an air monitoring network using air sensors
  - https://trackingcalifornia.org/cms/file/imperial-air-project/guidebook

- **Community in Action: A Comprehensive Guidebook on Air Quality Sensors**, South Coast Air Quality Management District (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC), September 2021
  - Guidebook for community organizations that covers planning for monitoring using sensors; sensor deployment, use, and maintenance; and data handling, interpretation, and communication
  - http://www.aqmd.gov/aq-spec/special-projects/star-grant

- **Air Sensor Stories**, University of Rochester, University of North Carolina at Chapel Hill, University of Texas Medical Branch, Columbia University, and WE ACT for Environmental Justice, 2018
  - Workshop guide and supporting materials to assist diverse audiences understand the potential of air sensors in addressing community concerns about particulate matter pollution; includes an air monitoring action plan worksheet to help groups think through key questions
  - https://www.urmc.rochester.edu/environmental-health-sciences/community-engagement-core/projects-partnerships/air-sensor-stories-workshop.aspx

- **Appendix B: Questions to Consider When Planning for and Collecting Air Sensor Data, and Sharing Your Results** (*this document)*
  - Provides a list of questions for consideration to help sensor uses better plan, collect, and share data

A.3.2 Plan: Developing a Plan

- **Guidance for Quality Assurance Project Plans (QA/G-5)**, U.S. Environmental Protection Agency, EPA/240/R-02/009, December 2002
  - Provides guidance on developing a Quality Assurance Project Plan (QAPP), which is an important part of the planning process for air quality monitoring projects
  - https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

- **Examples for Citizen Science Quality Assurance and Documentation,** U.S. Environmental Protection Agency, EPA 206-B-18-001, March 2019
  - Collection of examples that provide tools and procedures to help community science organizations properly document the quality of data
  - https://www.epa.gov/sites/default/files/2019-03/documents/508_csqappexamples3_5_19_mmedits.pdf

- **Templates for Citizen Science Quality Assurance and Documentation**, U.S. Environmental Protection Agency, EPA 206-B-18-001, March 2019
  - Templates that provide tools and procedures to help properly document the quality of data
  - https://www.epa.gov/sites/default/files/2019-03/documents/508_csqapptemplates3_5_19_mmedits.pdf
  - *Editable templates*: https://www.epa.gov/citizen-science/quality-assurance-handbook-and-guidance-documents-citizen-science-projects

- **Community Science Air Monitoring**
  - Guidance, provided by the New Jersey Department of Environmental Protection Division of Air Quality – Air Monitoring, on using air sensors for community projects; includes approaches to using sensors, types of sensors available, interpreting sensor data, four types of sensor projects and data quality assurance plan templates for each, and other helpful links
  - https://www.nj.gov/dep/airmon/community-science.html

- **Air Quality Agencies**
  - Websites that provide a list of state, local, and/or tribal agencies that manage air quality
  - *U.S. Environmental Protection Agency*: https://www.epa.gov/aboutepa/health-and-environmental-agencies-us-states-and-territories
  - *National Tribal Air Association (NTAA)*: https://www.ntaatribalair.org/
  - *National Association of Clean Air Agencies (NACAA)*: https://www.4cleanair.org/agencies/
  - *Association of Air Pollution Control Agencies (AAPCA)*: https://cleanairact.org/about/

A.3.3 Plan: Selecting an Air Sensor

- **Chapter 4: Sensor Performance Guidance *(this document)***
  - Provides an overview of laboratory and field sensor performance evaluations; performance characteristics needed for spatiotemporal variability, comparison, and long-term trend NSIM applications; and U.S. EPA's recommendations for sensor testing protocols, performance metrics, and targets

- **Appendix C: Choosing Air Sensors *(this document)***
  - Provides checklists for: (1) what to look for in a sensor before buying, (2) what to look for in a sensor user manual, and (3) sensor maintenance to ensure proper functionality and reliable performance

- **Performance Testing Protocols, Metrics, and Target Values for Ozone Air Sensors – Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications**, U.S. Environmental Protection Agency, EPA/600/R-20/279. February 2021
  - Provides recommended testing protocols (field and laboratory), performance metrics (parameters used to describe sensor data quality), and target levels to evaluate ozone air sensors
  - https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=350784&Lab=CEMM

- **U.S. EPA's Performance Targets and Testing Protocols Website**
    - Summary of the U.S. EPA's research on recommended testing protocols, metrics, and target values for evaluating the performance of air sensors
    - https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

- **Air Quality Sensor Performance Evaluation Center (AQ-SPEC) of the South Coast Air Quality Management District (South Coast AQMD) Website**
    - Website for the AQ-SPEC program which conducts laboratory and field evaluations of air sensors and provides information to the public regarding actual sensor performance and the advantages and potential limitations of using air sensors. AQ-SPEC is operated by South Coast AQMD
    - http://www.aqmd.gov/aq-spec

- **The National Solar Radiation Data Base (NSRDB)**, Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby. *Renewable and Sustainable Energy Reviews* 89 (2018): 51-60
    - Paper reviews the complete package of surface observations, models, and satellite data used for the NSRDB – an open dataset of solar radiation and meteorological data over the United States and regions of the surrounding countries
    - https://www.sciencedirect.com/science/article/pii/S136403211830087X

A.3.4 Setup: Locating Sites for Air Sensors

- **U.S. Code of Federal Regulations (CFR), Title 40 (Protection of Environment), Chapter 1 (Environmental Protection Agency), Subchapter C (Air Programs), Part 58 (Ambient Air Quality Surveillance)**
    - Specifies the regulatory requirements for the U.S. ambient air quality monitoring network including quality assurance procedures for operating air quality monitors and handling data; methodology and operating schedules for monitoring instruments; criteria for siting monitoring instruments; and air quality data reporting requirements
    - https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-58#ap40.6.58.0000_0nbspnbspnbsp.e

- **Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II**, Ambient Air Quality Monitoring Program, U.S. Environmental Protection Agency, EPA-454/B-17-001, January 2017
    - Handbook provides additional information and guidance (including pollutant-specific spatial scale characteristics) to assist tribal, state, and local

monitoring organizations in developing and implementing a quality management system for the Ambient Air Quality Surveillance Program described in 40 CFR Part 58
    - https://www.epa.gov/sites/default/files/2020-10/documents/final_handbook_document_1_17.pdf

- **Air Quality Agencies**
    - Websites provide a list of state, local, and/or tribal agencies that manage air quality
    - U.S. Environmental Protection Agency: https://www.epa.gov/aboutepa/health-and-environmental-agencies-us-states-and-territories
    - National Tribal Air Association (NTAA): https://www.ntaatribalair.org/
    - National Association of Clean Air Agencies (NACAA): https://www.4cleanair.org/agencies/
    - Association of Air Pollution Control Agencies (AAPCA): https://cleanairact.org/about/

- **Blueprint for the Development and Implementation of Distributed Sensor Networks**, U.S. National Institute of Standards and Technology Global Cities Team Challenge Transportation SuperCluster
    - Blueprint that summarizes lessons learned, best practices, and research questions for developing and implementing sensor networks
    - https://static1.squarespace.com/static/5967c18bff7c50a0244ff42c/t/5ad7c41c758d464041c7e58a/1524089886422/Distributed_Sensor_Networks_Recommendations.pdf

- **U.S. EPA Guide to Siting and Installing Air Sensors**
    - Information and considerations for locating an air sensor in both outdoor and indoor locations
    - https://www.epa.gov/air-sensor-toolbox/guide-siting-and-installing-air-sensors

- **South Coast Air Quality Management District - Sensor Siting and Installation Guide**
    - Guidance on how to locate and install air sensors: http://www.aqmd.gov/aq-spec/resources/related-documents
    - English: http://www.aqmd.gov/docs/default-source/aq-spec/resources-page/aq-spec-sensor-siting-and-installation-guide_v1-0-(english).pdf
    - Spanish: http://www.aqmd.gov/docs/default-source/aq-spec/resources-page/sensor-siting-and-installation-guide_v1-0-(spanish).pdf

- **U.S. EPA Air Sensor Toolbox – Air Sensor Research Grants and Challenges Website**
    - Website provides information on grants and challenges related to air research and air sensors
    - https://www.epa.gov/air-sensor-toolbox/air-sensor-research-grants-and-challenges

A.3.5 Setup: Collocation and Correction

- **U.S. EPA Air Sensor Collocation Instruction Guide,** U.S. Environmental Protection Agency, Office of Research and Development
    - Resource provides background information, links to web-based supporting materials, and instructions for evaluating the performance of air sensors by comparing the measurements made by collocated sensors and reference instruments
    - https://www.epa.gov/air-sensor-toolbox/air-sensor-collocation-instruction-guide

- **U.S. EPA Air Sensor Collocation Macro Analysis Tool**
    - Excel-based tool that helps users compare data from air sensors to data from reference instruments
    - https://www.epa.gov/air-sensor-toolbox/air-sensor-collocation-macro-analysis-tool

- **Community in Action: A Comprehensive Guidebook on Air Quality Sensors,** South Coast Air Quality Management District (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC), September 2021
    - Guidebook for community organizations that covers planning for monitoring using sensors; sensor deployment, use, and maintenance; and data handling, interpretation, and communication
    - http://www.aqmd.gov/aq-spec/special-projects/star-grant

- **South Coast AQMD Low-Cost Sensor Data Analysis Guide**
    - Guide that provides some brief instructions to help community scientists interact with the data they are collecting as well as some questions to help guide their analysis
    - http://www.aqmd.gov/docs/default-source/aq-spec/star-grant/air-quality-sensor-data-analysis-guide.pdf?sfvrsn=6

A.3.6 Collect: Data Collection, Quality Assurance/Quality Control, and Data Management

- **AirSensor and DataViewer Tools (R package)**
  - AirSensor is an open-source R package that allows users to access historical data, add spatial metadata, and visualize community monitoring data through maps and plots
  - DataViewer is an interactive web application that incorporates the functionality and data plotting functions of the AirSensor for interpreting and communicating community data collected by sensor networks
  - https://github.com/MazamaScience/AirSensor/tree/version-0.5
  - https://github.com/MazamaScience/AirSensorShiny
  - These papers summarize the development and enhancements of the AirSensor and DataViewer tools:
    - Feenstra et al, 2020 https://doi.org/10.1016/j.envsoft.2020.104832
    - Collier-Oxandale et al, 2022 https://doi.org/10.1016/j.envsoft.2021.105256

- **Data Policies for Public Participation in Scientific Research: A Primer**, DataONE Public Participation in Scientific Research Working Group, August 2013
  - Guide that introduces data policies in the context of public participation in scientific research or community science, provides examples, and best practices for implementing data polices in community science projects
  - https://safmc.net/wp-content/uploads/2016/06/Bowseretal2013_DataPolicyPrimer.pdf

- **Handbook for Citizen Science Quality Assurance and Documentation**, U.S. Environmental Protection Agency, EPA 206-B-18-001, March 2019
  - Handbook that covers common expectations for quality assurance and documentation and best management practices to level the playing field for organizations that train and use volunteers in the collection of environmental data
  - https://www.epa.gov/sites/default/files/2019-03/documents/508_csqapphandbook_3_5_19_mmedits.pdf

- **Data Management Guide for Public Participation in Scientific Research**, DataONE Public Participation in Scientific Research Working Group, February 2013
  - Guide that provides best practices and other considerations for data management along the life cycle of community science projects
  - https://www.dataone.org/sites/all/documents/DataONE-PPSR-DataManagementGuide.pdf

- **USGS Guide to Data Management**
    - United States Geological Survey (USGS) website that provides guidance, best practices, and tools for data management including in-depth training modules and numerous data management example scenarios
    - https://www2.usgs.gov/datamanagement

- **Survey Report: Data Management in Citizen Science Projects**, Chade S and Tsinaraki C., Publications Office of the European Union, JRC101077, 2016
    - Report summarizes the findings from a Joint Research Centre (JRC) survey of community science projects completed primarily in European Union (EU) countries
    - https://publications.jrc.ec.europa.eu/repository/handle/JRC101077

- **Citizenscience.gov Website**
    - Government website that promotes crowdsourcing and citizen science across the U.S, government; website catalogs government supported community science projects, provides a toolkit to assist with project design and maintenance, and serves as a gateway for community science practitioners and coordinators across the government
    - https://www.citizenscience.gov/#

- **U.S. EPA Guidance on Environmental Data Verification and Data Validation**, U.S. Environmental Protection Agency, EPA/240/R-02/004, November 2002
    - Guidance document that specifies the agency-wide program for environmental data QA and includes practical advice to individuals implementing data verification and data validation
    - https://www.epa.gov/sites/production/files/2015-06/documents/g8-final.pdf

A.3.7 Evaluate: Analyzing, Interpreting, Communicating, and Acting on Results

- **Personal Strategies to Minimise Effects of Air Pollution on Respiratory Health: Advice for Providers, Patients and the Public,** Carlsten C., S. Salvi, G.W.K. Wong, K.F. Chung. *European Respiratory Journal* 55(6), 2020
    - Paper provides guidance based on findings from published literature to assist health care providers, patients, public health officials, and the public to reduce exposure to indoor and outdoor air pollution
    - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7270362/

- **The AirSensor Open-source R-package and DataViewer Web Application for Interpreting Community Data Collected by Low-cost Sensor Networks**, Feenstra B., A. Collier-Oxandale, V. Papapostolou, D. Cocker, and A. Polidori. *Environmental Modelling & Software* 134, 2020
  - Paper summarizes the development of two software systems to assist in visualizing and understanding air sensor data collected by community networks. *AirSensor* is an open-source R package that allows users to access historical data, add geospatial metadata, and visualize community monitoring data using maps and plots. *DataViewer* is an interactive web application that incorporates the functionality and data plotting functions of *AirSensor* for interpreting and communicating community data collected by low-cost sensor networks
  - https://www.sciencedirect.com/science/article/pii/S1364815220308896

- **AirSensor v1.0: Enhancements to the Open-Source R Package to Enable Deep Understanding of the Long-Term Performance and Reliability of PurpleAir Sensors**, Collier-Oxandale A., B. Feenstra, , V. Papapostolou, and A. Polidori. *Environmental Modelling & Software* 148, 2022
  - Paper describes the enhancements made to the open-source R package AirSensor (version 1.0) and the web application DataViewer (version 1.0.1). to support data access, processing, analysis, and visualization for the PurpleAir PA-II sensor. The paper also demonstrates how the enhancements help track and assess the health of air sensors in real-time and historically
  - https://www.sciencedirect.com/science/article/pii/S136481522100298X

- **Understanding Social and Behavioral Drivers and Impacts of Air Quality Sensor Use,** Hubbell B.J., A. Kaufman, L. Rivers L, K. Schulte, G. Hagler, J. Clougherty, W. Cascio, and D. Costa. *Science of the Total Environment* 621 (2018): 886-894
  - Paper discusses the social science research conducted on air sensor use and identifies: (1) research opportunities between the social and environmental sciences and the entities involved in developing, testing, and deploying air sensor technologies; (2) the challenges associated with sensor data generation, interpretation, and analysis; and (3) collaboration opportunities for communities and organizations to better understand the reasons and approaches for using sensors and how technological innovations may improve the ability to reduce exposures to air pollution
  - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6705391/

- **A Visual Analytics Approach for Station-Based Air Quality Data,** Du, Y., C. Ma, C. Wu, X. Xu, Y. Guo, Y, Zhou, and J. Li. *Sensors* 17(1), 2016
  - Paper proposes a comprehensive visual analysis system (*AirVis*) for air quality analysis that integrates several visual methods, such as map-based views, calendar views, and trends views, to analyze multi-dimensional spatiotemporal air quality data
  - https://www.mdpi.com/1424-8220/17/1/30/htm

- **AtmoVis: Visualization of Air Quality Data,** Powley, B., Master of Science Thesis, Victoria University of Wellington, New Zealand, 2019
  - Document discusses the results from a search of literature regarding systems and methods for visualizing and evaluating air pollution and presents AtmoVis – a web-based system that includes visualizations for site view, line plot, heat calendar, monthly rose, monthly averages, and data comparisons
  - https://homepages.ecs.vuw.ac.nz/~djp/files/MSc_BenPowley_2019.pdf

- **Openair – An R Package for Air Quality Data Analysis,** Carslaw, D.C. and K. Ropkins. *Environmental Modelling & Software* 27-28, 2012
  - *Openair* is an R package used extensively in academia and in the public and private sectors that analyzes air quality data and atmospheric composition data
  - https://davidcarslaw.github.io/openair
  - https://bookdown.org/david_carslaw/openair/

- **U.S. EPA Real Time Geospatial Data Viewer (RETIGO)**
  - REal TIme GeOspatial Data Viewer (RETIGO) is a free, web-based tool that can be used to explore stationary or mobile environmental data that you have collected; nearby public air quality and meteorological data can be added to the display
  - https://www.epa.gov/hesc/real-time-geospatial-data-viewer-retigo

- **U.S. EPA AirData: Air Quality Data Collected at Outdoor Monitoring Stations Across the U.S.**
  - A website providing tools and access to recent and historical air quality information for the U.S., Puerto Rick, and the U.S. Virgin Islands; view data on an interactive mapping application; obtain information about each monitor; and download daily and annual concentration data, AQI data, and speciated particle pollution data (primarily from U.S. EPA's Air Quality System database)
  - https://www.epa.gov/outdoor-air-quality-data

- **Community in Action: A Comprehensive Guidebook on Air Quality Sensors,** South Coast Air Quality Management District (South Coast AQMD), Air Quality Sensor Performance Evaluation Center (AQ-SPEC), September 2021
    - Guidebook for community organizations that covers planning for monitoring using sensors; sensor deployment, use, and maintenance; and data handling, interpretation, and communication
    - http://www.aqmd.gov/aq-spec/special-projects/star-grant

- **California Air Resources Board (CARB) List of CARB-Certified Air Cleaning Devices**
    - A website providing a table of CARB-certified air cleaning devices, a description of the difference between mechanical and electronic air cleaners, and resources to help you select a safe and effective air cleaner
    - https://ww2.arb.ca.gov/list-carb-certified-air-cleaning-devices

- **U.S. EPA Research on Do-It-Yourself (DIY) Air Cleaners to Reduce Wildfire Smoke Indoors**
    - A website providing on overview of EPA research conducted to evaluate the safety and effectiveness of DIY air cleaners; includes a summary and links to the Underwriters Laboratories (UL) safety report findings, answers to frequently asked questions, and links to helpful resources
    - https://www.epa.gov/air-research/research-diy-air-cleaners-reduce-wildfire-smoke-indoors

A.4 Sensor Performance Guidance

A.4.1 Sensor Performance Evaluations

- **U.S. EPA Air Sensor Performance Evaluations**
    - Collection of results for field and laboratory evaluations of air sensors conducted by U.S. EPA Office of Research and Development
    - https://www.epa.gov/air-sensor-toolbox/evaluation-emerging-air-sensor-performance

- **South Coast Air Quality Management District (South Coast AQMD) Air Quality Sensor Performance Evaluation Center (AQ-SPEC)**
    - Field and laboratory evaluations of commercially available air sensors conducted by AQ-SPEC
    - http://www.aqmd.gov/aq-spec

- **European Commission Joint Research Centre (JRC)**
  - Results for field and laboratory evaluations of air sensors primary in the form of scientific journal articles and reports
  - https://publications.jrc.ec.europa.eu/repository/

- **AirParif AIRLABS Microsensors Challenge**
  - Results from an international challenge that promotes innovation and helps inform users on the performance of air sensors in different applications
  - http://www.airlab.solutions/en/projects/microsensor-challenge

A.4.2 Approaches Used to Evaluate Sensor Performance

- **U.S. EPA Performance Testing Protocols, Metrics, and Target Values for Air Sensors – Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications**
  - Reports that provide recommended testing protocols (field and laboratory), performance metrics (parameters used to describe sensor data quality), and target levels to evaluate air sensors that measure criteria air pollutants
  - https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

- **ASTM WK64899 "New Practice for Performance Evaluation of Ambient Air Quality Sensors and Other Sensor-Based Instruments"**
  - Provides information on a practice for evaluating the performance of air quality sensors in ambient air
  - https://www.astm.org/workitem-wk64899

- **EU/CEN/TC 264/WG 42 "Air quality – Performance evaluation of air quality sensor systems – Part 1: Gaseous pollutants in ambient air"**
  - Outlines testing procedures and requirement for classifying performance of air quality sensors for the monitoring of gaseous pollutants
  - https://www.en-standard.eu/pd-cen-ts-17660-1-2021-air-quality-performance-evaluation-of-air-quality-sensor-systems-gaseous-pollutants-in-ambient-air/

- **Air Quality Sensor Performance Evaluation Center (AQ-SPEC) of the South Coast Air Quality Management District (South Coast AQMD) Website**
  - Website for the AQ-SPEC program which describes how field and laboratory tests are conducted
  - Field Evaluation Protocol and Reports: http://www.aqmd.gov/aq-spec/evaluations/field
  - Laboratory Evaluation Protocol and Reports: http://www.aqmd.gov/aq-spec/evaluations/laboratory

A.4.3 Summarizing Sensor Performance Evaluation Results using U.S. EPA's Targets Reports

- **U.S. EPA Performance Testing Protocols, Metrics, and Target Values for Air Sensors – Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications**
  - Reports that provide recommended testing protocols (field and laboratory), performance metrics (parameters used to describe sensor data quality), and target levels to evaluate air sensors that measure criteria air pollutants
  - Appendices of the Targets Reports provide standardized reporting templates
  - https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

- **U.S.-EPA developed *sensortoolkit* python code library**
  - Code library for evaluating air sensor data collocated with reference instruments; code can be used to calculate performance metrics
  - GitHub: https://github.com/USEPA/sensortoolkit
  - PyPI: https://pypi.org/project/sensortoolkit/

- **U.S.-EPA $PM_{2.5}$ Continuous FEM Monitor Comparability Assessments**
  - Tool providing a one-page technical report that assesses the comparability of a $PM_{2.5}$ continuous FEM monitors when collocated with an FRM sampler
  - https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments

Appendix B: Questions to Consider When Planning for and Collecting Air Sensor Data, and Sharing Your Results

Getting input from others before you start collecting measurements will help you better plan and collect data to meet your purpose. Below we provide a list of the types of questions to consider. While this list is by no means exhaustive, answering these questions helps you plan and ensures credibility in your data and results. These questions can also help you respond to inquiries from others if you decide to share your plans, data, and results.

B.1 Planning (see Section 3.3)

- What is the purpose of the project and the question you want to answer?
- What existing research and data are available to help answer your question?
- What actions might you take depending on the research, data, or air monitoring results?
- What pollutants will you measure? If you are interested in a particular source of air pollution, have you checked that your selected pollutant is relevant to that source (see *Table 2-1*)?
- Have you developed a plan for your monitoring activities (see *Section 3.3*)?
- What are the expected levels for the pollutant in the location of interest, including background and peak concentrations, seasonal and day/night trends, and spatial variability?
- Do you have procedures and instructions so that measurements are taken in a consistent way (e.g., develop standard operating procedures)?
- Have you established clear roles and responsibilities for those involved in your monitoring activities?

B.2 Working with Governmental Officials (see Section 3.3 and Section 3.8.2)

- Will you contact the state/local/tribal air monitoring agency during the planning phase to obtain their input and recommendations?
- Will you consider alternative ways to answer the questions using other data sources besides air sensors (e.g., traffic counts, health data, existing monitoring data)?
- Have you clearly defined your purpose for monitoring and expected outcomes? Is collecting air sensor data the best way to achieve these outcomes?
- Are you expecting any agencies (local/state/federal/tribal) to use your data or results? Have you spoken with the agencies to understand if that is possible?
- Have you filed a formal complaint with your state/local/tribal air quality agency or other responsible organization (e.g., the department of health, fire department)?

B.3 Setting up Monitoring Locations (see Section 3.5)

- Where will you collect the measurements?
- What will be the location of the sensor(s) (e.g., latitude, longitude, elevation, and height of the sensor from ground level)?
- Will any obstructions nearby affect the airflow around the sensor?
- How will you select the site? What criteria or guidelines will you use?
- What nearby emission sources (e.g., roadways, industrial facilities) might affect the sensor measurements?
- Are there other potential local sources near your site (e.g., dust from unpaved roads, parking areas, street-sweeping activity) that might affect your measurements?
- Might anyone nearby be smoking (e.g., cigarettes, cigars) when and where you are collecting the measurements?
- Will there be any periodic events (e.g., construction, fireworks, fires) that could affect the data?
- What type of conditions will the measurements represent (e.g., outdoor, indoor, occupational – see *Section 2.3*)?

B.4 Collecting Data (see Section 3.7)

- What instrument/sensor will you use (i.e., manufacturer, model, etc.)? Will these be new devices, older, or refurbished?
- How long will you make your measurements (e.g., two weeks, two months)?
- Will you take the measurements at a fixed site or mobile platform (e.g., on a car, on a person)? What type of environmental conditions will they represent?
- Will you receive adequate training on operating the device, maintaining it, and troubleshooting any issues?
- Will you use a lab notebook, log sheets, or check lists to record instrument set up, maintenance, and other additional data? Will these be in paper or electronic formats? Where will this information be stored and who will have access?
- Will you collocate (i.e., place nearby) your sensor near reference monitors or other trusted measurement systems to evaluate their performance? If so, where will you collocate and how will you process and show your results?
- Will you make any adjustments, corrections, or calibrations to the data after collection? Will you document the methods and techniques used?
- How will you estimate the precision and bias of your air sensor data?
- Will you read the data from the screen or store it in an electronic format?
- If applicable, how will you name the data files so that you can keep track of where and when they were collected? How will you keep and protect raw, unedited data from the sensors? How will you document how data was processed or corrected? How will you track the data if you transfer it to others to analyze?
- What, if any, additional local data or observations will you collect (e.g., wind measurements, site photos, global positioning system (GPS) coordinates, activity logs, event logs, health information)?

- What, if any, additional data sources will you draw from (e.g., meteorological data from the National Weather Service, regulatory air monitoring data from a state/local/tribal air monitoring agency)? Where will those data come from and how will they be integrated with the measurements you are making?
- What type of file or database will you use to store the data?
- How will you ensure that each parameter has the correct units?
- How will you document the time standard [e.g., local standard time (LST), Coordinated Universal Time (UTC)]?

B.5 Conducting Quality Control (see Section 3.7.2)

- What procedures will you use to ensure that the sensors measure high-quality data?
- Will you develop quality control (QC) criteria that the sensor data must meet?
- Will you have Standard Operating Procedures (SOPs) (i.e., detailed written instructions and directions on how to perform a technical activity so that measurements are obtained in a consistent way)?
- Will you average the data, and if so, how? How will you account for missing data, negative values, and extreme outliers?
- What software will you use to process and QC your data (e.g., Microsoft Excel)?
- How will you correct or adjust the air sensor data?
- How will you document any changes or adjustments to the data?
- Will you use consistent data qualifiers to “flag” data that do not meet QC criteria?
- Will you document if there are any persistent problems with the data or significant downtime?
- How will you record and resolve any data problems?

B.6 Evaluating Data (see Section 3.8)

- Do you need software to analyze the data (e.g., Microsoft Excel, R, Matlab, Python)? Does someone on your team have the skills needed to use the required software?
- How will you analyze the data (e.g., create a scatterplot, create a time series plot, compare with meteorological measurements)?
- How will you differentiate the source you are trying to measure from the background pollutant concentrations?
- Will you publish your results or create any public communication materials?

B.7 Other

- Do you have any interaction (past, present, or future) with the entity potentially responsible for creating the emissions?
- Will there be any limitations or restrictions for using your data?
- Who will be the primary contact if others have questions about the data?
- Is there additional support that would be helpful (e.g., data analysis or interpretation support, collocation assistance)?

Appendix C: Checklists

C.1 What to Look for in an Air Sensor?

Before buying an air sensor, use this checklist to help make sure you are purchasing a sensor that meets your needs and produces data suitable for your application.

☐ **Sensor accuracy**

Look for a sensor with demonstrated and documented performance under similar environments and operating conditions that you anticipate encountering in your monitoring application. Accuracy consists of precision and bias (see Section 3.6 and Chapter 4).

☐ **Pollutants of interest**

Purchase sensors that can accurately detect the pollutants of interest with limited interferences from weather conditions or other pollutants (see Section 3.4, Table 2-1, and Table 2-2).

☐ **Detects high and low concentrations**

Because pollutant concentrations can vary greatly, you will need to determine if a sensor can detect a pollutant at the low-end of the concentration range and the range's high end. See Table 2-1 for typical pollutant concentration ranges.

☐ **Reliability**

The sensor(s) you select should be able to operate for extended periods with no or minimal maintenance. Consider the warranty and replacement policy of the manufacturer to ensure uninterrupted operation.

☐ **Instructions or user guide**

Operation and maintenance instructions from the manufacturer enable you to set up, conduct routine maintenance, fix and repair, and replace the sensors as needed. Instructions may also be provided for zeroing or calibrating the sensor or for quality assuring, correcting, or processing of the data. Instructions should also include how to access both real-time and historical data.

☐ **Power**

Give careful consideration to the power requirements of the sensor. Power requirements vary from plug-in, battery, or solar power and will depend on a user's application. Plug-in devices are best suited for stationary monitoring applications; however, make sure power is available and easily accessible. Battery-powered devices are best for mobile applications or short-term data collection activities. Solar-powered devices require proper size (of the solar panel and battery) and adequate orientation to sunlight. The choices and logistics are involved – plan enough time to ensure that you can identify a solution that meets your needs.

- [ ] **Data Transmission**

Many options exist for air sensor data communication from the sensor to the sensor data repository and include cellular, WiFi, Bluetooth, satellite, low-power wide-area network (LoRa), or other methods. Remember that you may want to test the communications at the actual site and inquire about ongoing costs associated with communicating data via cellular and other protocols. Ensure that you have the ability to enable the necessary settings on your computer and/or WiFi network to allow you to use the selected data transmission option (if applicable).

- [ ] **Transparent data processing**

Sensor data often undergo processing, correction or adjustments, and averaging to improve quality. Look for sensor manufacturers that provide descriptions of the methods and approaches they use to process sensor data, especially related to sensor data correction (sometimes called calibration) techniques. Section 3.6 discusses the calibration and correction methods and procedures.

- [ ] **Customer service**

Seek to understand how responsive and knowledgeable the company will be to your questions and needs. Consider the company's location (e.g., time zone), contact methods (e.g., phone, email), and specific services they offer.

- [ ] **Ease-of-use**

Look for intuitive and easy-to-use sensors and software to manage the data the air sensor produces. Match the sensor's features with your needs. These features could include weatherproofing, durability for handheld and mobile sensors, on-sensor display (e.g., lights or digital readout), data management capabilities, etc.

- [ ] **Data Handling and Access**

Determine how data processes and where it is stored and in what format. Identify the data management system used to ingest, process, visualize, and distribute data. Determine who can access the data, who has ownership rights of the data, privacy terms, how long will the data be available.

- [ ] **Cost**

The cost of sensor technology may vary greatly depending on the pollutant measured and the degree of accuracy and sensitivity the user needs. Consider the initial purchase price and the long-term operational costs, such as data transmission and storage, maintenance, calibration services, data ownership, and repairing or replacing sensor components.

C.2 What to Look for in a User Manual?

A user manual should be comprehensive and clear and effectively describe the installation, operation, and maintenance activities needed so that you can set up and run the sensor optimally. Without a good user manual, you may have to spend more time figuring out how to operate, troubleshoot, and/or repair your sensor. Request a user manual before purchasing a sensor to ensure the device meets your needs. The following are recommended items to look for in a user manual:

- [ ] **Performance specifications**

  The manual should include details about the sensor's accuracy, range of measurement, minimum and maximum detection limits, sampling frequency, ambient temperature range, power requirements, response time (i.e., how quickly the sensor responds to changing conditions), sensor lifespan or expiration date, etc. Demonstrations of sensor performance in real-world applications (ideally, independent reports or scientific articles discussing sensor evaluation test results) are also very important. *Chapter 4* provides more details about air sensor performance.

- [ ] **Installation instructions**

  The manual should provide the procedures that describe where and how to install the sensor and check that it is operating correctly.

- [ ] **Operating instructions**

  Details about how to ensure the sensor is running correctly and how to access its data are critically important for a user manual.

- [ ] **Maintenance requirements**

  The manual should include a list of the activities, requirements, and specific frequencies or schedule at which they must be performed. See *Appendix C.3* for more information regarding sensor maintenance.

- [ ] **Correction (sometimes called Calibration)**

  The manual should provide details about the process and method used to adjust or correct data. Providing more information about the data correction helps build trust and confidence in the data and the air sensor.

- [ ] **Data access**

  Look for details about how to view real-time and historical data, access backup raw and processed data, and share data with other organizations. A user manual should identify any data ownership terms and conditions and data privacy terms.

- [ ] **Interferences**

  The manual should clearly describe the known (and potential) interfaces from weather conditions (e.g., high humidity) and other pollutants in the air.

- [ ] **Customer service**

  Look for support information with contact details (e.g., methods, hours of operation) and what is covered (or not covered) with customer support.

- [ ] **Limitations**

  The manual should describe restrictions or limitations of the sensors and its operation and explicitly identity what is covered by the warranty.

- [ ] **Hazard Warnings**

  Check to see if the user manual provides any warnings concerning any hazards or potential hazards that might be present during installation, calibration, operation, maintenance, or troubleshooting of the sensor.

C.3 How to Maintain Your Air Sensor?

Like most other forms of technology, air sensors require maintenance to ensure proper functionality and reliable performance. These preventative actions associated with maintenance are necessary for both short- and long-term operations. By properly caring for an air sensor, you can reduce errors in data collection, extend the operating life of the device, and save money that would otherwise be spent on replacement parts and repair services.

Check with the air sensor manufacturer for protocols to maintain your device so it operates properly and produces good data. Typical routine maintenance processes include:

- ☐ Cleaning of internal and external surfaces and components to prevent the buildup of bugs, dust, pollen, etc.
- ☐ Replacement of filters and other consumables.
- ☐ Replacement of the sensor when it fails or reaches the end of its service lifespan.
- ☐ Replacement of rechargeable batteries.
- ☐ Cleaning off dust and dirt from solar panels.
- ☐ Collocation and correction of sensor data to improve data quality (see Section 3.6).
- ☐ Visual inspection of data to identify 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.
- ☐ Inspection of the sensor placement location to ensure that no significant changes have occurred (e.g., tree growth, building changes, new local sources of pollutants).
- ☐ Development and maintenance of a logbook to ensure maintenance occurs at regular intervals.

Appendix D: Data Handling and Air Quality Index (AQI) Calculations

D.1 Data Processing

Working with data consists of reviewing and calculating values from the data to produce meaningful information. With air sensors, data processing can be a very time-consuming process because sensors can produce lots of data. For example, an air sensor network of 10 sites, with each site measuring two pollutants every minute, can produce over 5.3 million data values over a one-year period. In contrast, a similar size network producing hourly data only generates about 220,000 data values. Thus, it takes time to process the data to glean insights, meaning, and information from the results. Software and planning can help you efficiently and effectively process data. This section provides some tips for processing data by harmonizing and aggregating the data.

When harmonizing data, you ensure that the data is of good quality and complete and are comparable to other datasets. By aggregating (e.g., averaging, compiling) data, you can notice the big-picture trends and see patterns in the data. For example, if you want to review 1 week of air sensor data, you might want to aggregate the 1-minute values by making hourly averages and viewing those data to see the trends. This aggregation results in reviewing 168 hourly averaged data points instead of over 10,000 1-minute data points. Once you see the "big picture," you can start looking at the details in the 1-minute data.

What are Some Important Definitions Related to Data Processing?

Data management is a collection of procedures needed to acquire, process, and distribute data.

Data harmonization is the process of reviewing data for quality and completeness, and then combining the data for querying and viewing.

Data aggregation is the process of compiling information to prepare combined datasets for data processing.

When deciding how to view the data, consider your monitoring question. Some averages will be more relevant to your investigation than others. For example, a project interested in changes in air pollution before, during, and after school drop-off may find 5 or 10-minute averages useful. A project focused on seasonal changes in air quality (e.g., residential wood burning) may find weekly or monthly averages helpful.

When you compare data with standards, you will need to aggregate the data similar to the aggregation required by the standard. For example, for fine particulate matter ($PM_{2.5}$) data, you will need to calculate a 24-hour average from the hourly data before comparing it to the 24-hour National Ambient Air Quality Standards (NAAQS).

D.1.1 Data Quality Assurance (QA)

Data harmonization consists of the steps to prepare data for aggregation and subsequent data analysis. Air sensor data may have issues that that need data cleaning. By reviewing the data and addressing these problems, your data will be more trustworthy and resulting analyses and conclusions will be more robust. Here are some suggestions to help harmonize your data:

1. **Quality control check and validate** data by reviewing it using time series plots, spatial plots, and statistical summaries to identify questionable data. Section 3.7.1 and 3.7.2 of this Guidebook discusses data review and quality control checks you can apply.
2. **Identify outliers** or data points that are significantly different from other data values. Outliers are typically easy to see in a time series plot of data (Figure D-1). It is typically easier to find outliers in higher-time resolution data (e.g., 1-minute) rather than averaged data (e.g., 1-hour and 24-hour averages). Identify these outliers and decide whether or not to include them from data aggregation and analysis steps.
3. **Address negative values** which can occur because air sensors and instruments have uncertainty, and at near-zero concentrations, you might see some slightly negative values (e.g., -0.5 µg/m^3). These slightly negative values may be valid and you may wish to retain these values (consult the sensor manufacturer for guidance). However, significant or persistent negative values likely indicate a problem with the air sensor or instrument, and you should flag these values and exclude them from subsequent data processing and analysis.
4. **Address missing data** which may occur when air sensors do not collect data due to power outages, sensor malfunctions, loss of communications, etc. Some missing data is common when using air sensors, but too much missing data means the data and averages of the data will not represent actual air quality conditions. It is recommended that you do not replace or fill in missing data with estimated values (e.g., interpolated or extrapolated concentrations). Instead, seek to understand and fix the problem causing the missing data.
5. **Evaluate data completeness** to ensure that enough data exist to represent air quality conditions during that monitoring period. Completeness is a measure of the amount of valid data obtained from a sensor compared to the amount expected to be obtained under correct, normal conditions. Generally, at least 75 percent of the data are needed to make a valid average (e.g., at least 45, 1-minute measurements are needed to make a valid 1-hour average). When the 75 percent completeness criterion is met, the resulting aggregation is usually considered representative of that monitoring period.

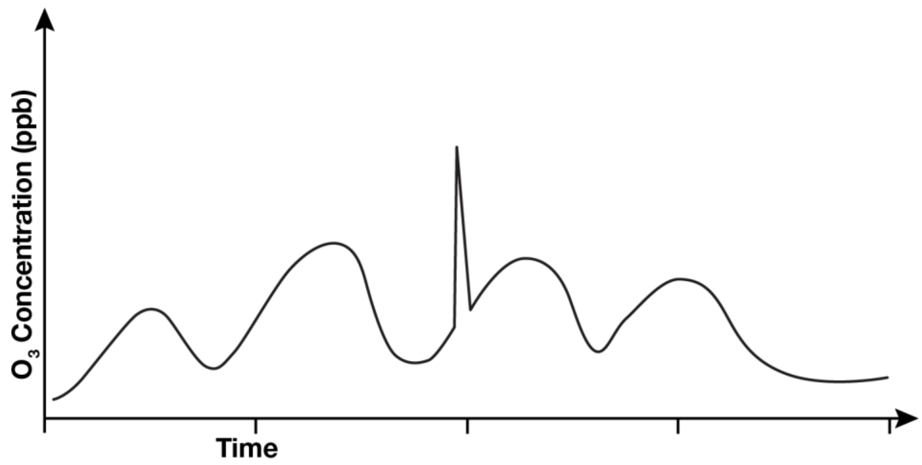


Figure D-1. Time Series of Ozone (O_3) Concentrations Showing a "Spike" in Concentration that is an Outlier in the Data

D.1.2 Data Aggregation

Data aggregation helps with the analysis and assessment of data by averaging, counting, or filtering data. This process allows you see the more prominent trends in your data and enables you to compare the aggregated values to standards and indexes. The most common aggregation methods include:

- Averages of air quality data are typically calculated over a time period that ranges from minutes to a year. There are several types of averages, as shown in Figure D-2.

  a. Block average is a technique to reduce data points to a particular period by computing the mean. For example, 24 hourly measurements of $PM_{2.5}$ can be averaged into a single 24-hour value that represents the mean $PM_{2.5}$ concentration during that period. This type of averaging helps reduce the number of data values you need to examine and can enable comparison to standards like the NAAQS.

  b. Rolling (moving) average is a technique to obtain an overall idea of the trends in a data set and "smooth" some of the rapid changes. You can calculate it for any period that corresponds to a standard or index (e.g., Air Quality Index, AQI). Typically, rolling average periods are 24 hours for $PM_{2.5}$ and PM_{10}, 8 hours for ozone (O_3), and 3 months for lead (Pb).

A 24-hour rolling average on 1-hour data would result in 24 rolling averages over a 24-hour period, while block averaging would result in only 1 block average.

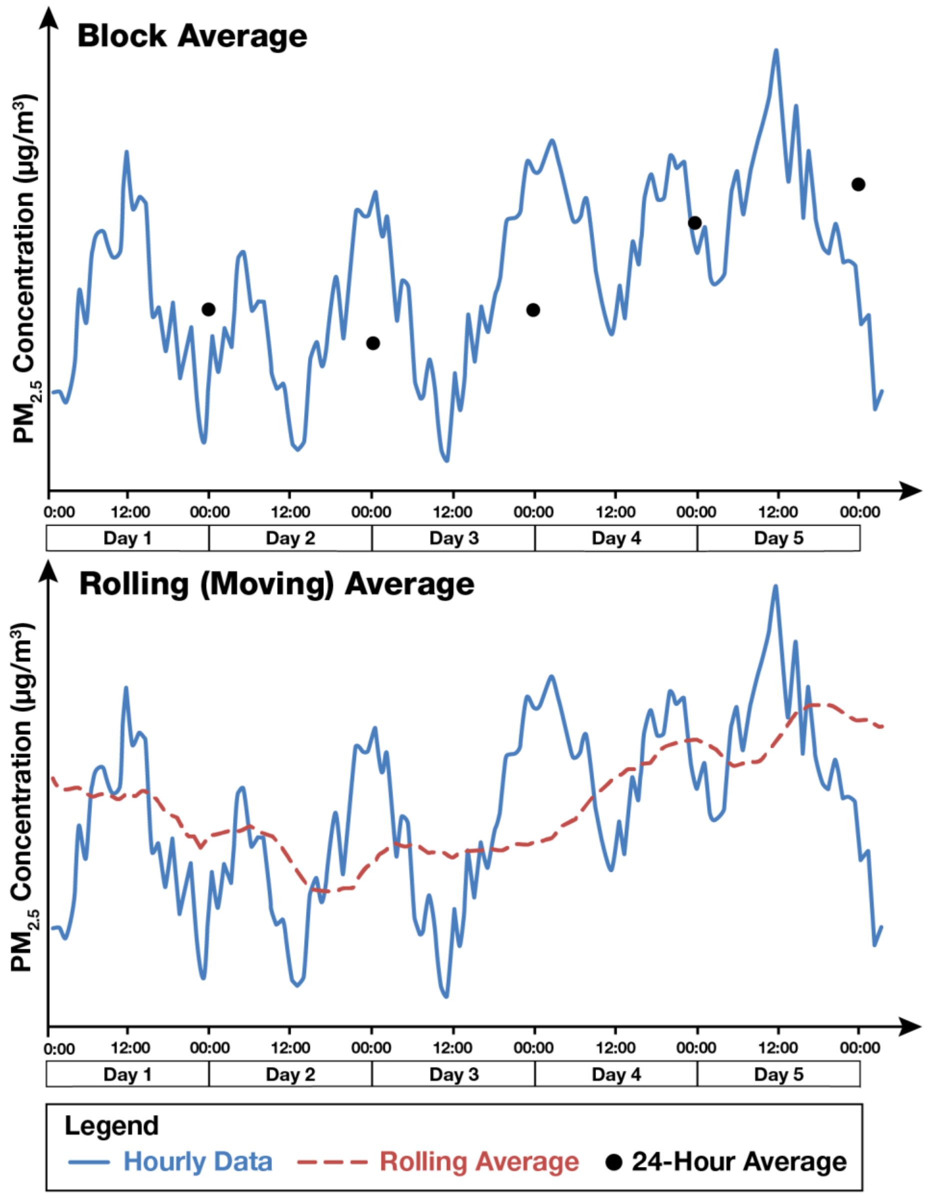


Figure D-2. Time Series Showing Raw $PM_{2.5}$ Data with Block and Rolling Averages

- **Counting** is a method to characterize air quality conditions by summarizing the number of "events" that occur above a threshold. For example, you might want to count the number of days where the 8-hour average O_3 concentrations are above 70 ppb, which is "Unhealthy for Sensitive Groups" on the AQI scale. You could also count the number of days when $PM_{2.5}$ averages fall within a specific category of the AQI (e.g., number of "Good" days). The exact counting method will depend on your application, but could include counting the number of hours, days, or sites above a specific concentration.

- **Filtering or stratifying data** is a method to subset data by time or location. This type of filtering allows you to see differences in aggregations that might result from factors such as weather or emission events (e.g., high traffic times, wildfires). You might also consider filtering by time (e.g., hour, day, weekday/weekend, season). For example, comparing averages of nitrogen dioxide (NO_2) concentrations by the hour of the day and by weekday and weekend may show the effect of traffic activity on local pollution conditions.

Tip: Consider ways that can make data processing less time-consuming and easier

Plan ahead *as processing data can be very time-consuming. This planning will save you effort and reduce the chances that data need to be re-measured or reprocessed.*

Match the aggregation methods *(e.g., averaging period) when comparing air sensor data to other datasets, standards, or indices.*

Use software to facilitate data processing*. Consider the costs of software. Some software is free, whereas other software is not. A data management system (see Section 3.7.3 of this Guidebook) and other analysis software (see Section 3.8 of this Guidebook) can help process data.*

D.2 AQI Calculations

D.2.1 Background

The Air Quality Index (AQI) is U.S. EPA's index for communicating daily air quality. It provides statements for each category that tell you about air quality in your area, which groups of people may be affected, and steps you can take to reduce your exposure to air pollution. The AQI is calculated for five of the six criteria pollutants: O_3, PM (including $PM_{2.5}$ and PM_{10}), CO, NO_2, and SO_2.

Are There Other Air Quality Indices in Different Countries?

Yes! Other countries have established different air quality indices. Some examples include:

- Air Quality Health Index (Canada)
- Air Quality and Health Risk Index (Mexico)
- Air Pollution Index (Malaysia)
- Pollutant Standards Index (Singapore)
- European Air Quality Index (European Union)

The AQI scale runs from 0 to 500, with higher AQI values indicating more hazardous levels of air pollution and associated health concerns. For each pollutant, an AQI value of 100 generally corresponds to an ambient air concentration equal to the level of the short-term NAAQS for protection of public health. AQI values at or below 100 are generally considered to be satisfactory. For example, an AQI value of 50 or below represents "Good" air quality, while an AQI value over 300 represents "Hazardous" air quality.

The AQI is divided into six color-coded categories, as shown in Table 2-5, with each category corresponding to a different level of health concern. The color-coding allows the public to quickly determine whether air quality is reaching unhealthy levels in their communities. The specific concentration breakpoints for each of the six levels vary by pollutant.

Although the AQI color scale is required by law [40 Code of Federal Regulations (CFR) Part 58.50 and 40 CFR Appendix G to Part 58], it is recognized that the colors may not be accessible to all people. The South Coast Air Quality Management District (AQMD) developed a modified version of the AQI color scale that accommodates individuals with color vision deficiencies. The modified scale was tested against eight common color impairments and remains distinguishable in grayscale. Currently, the modified colors are being piloted under the “View More Accessible AQI Colors” option on South Coast AQMD’s real-time air quality map and the ColorVision Assist option on the AirNow Fire and Smoke Map.

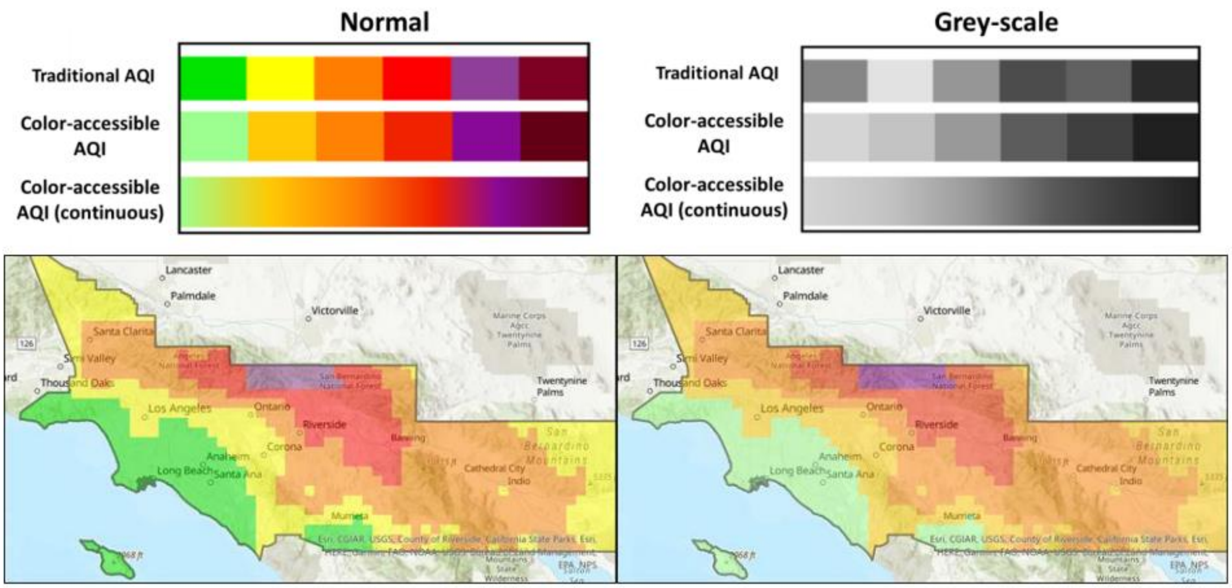


Figure D-3. Comparison of the Traditional AQI and Color-Accessible AQI Color Scale Presented in Color, Grey-Scale, and on a Map of the South Coast Air Basin (South Coast AQMD Press Release – May 2022)

D.2.2 Computing the AQI

This section explains how to calculate the AQI. Figure D-4 shows a flowchart of the process for computing the AQI.

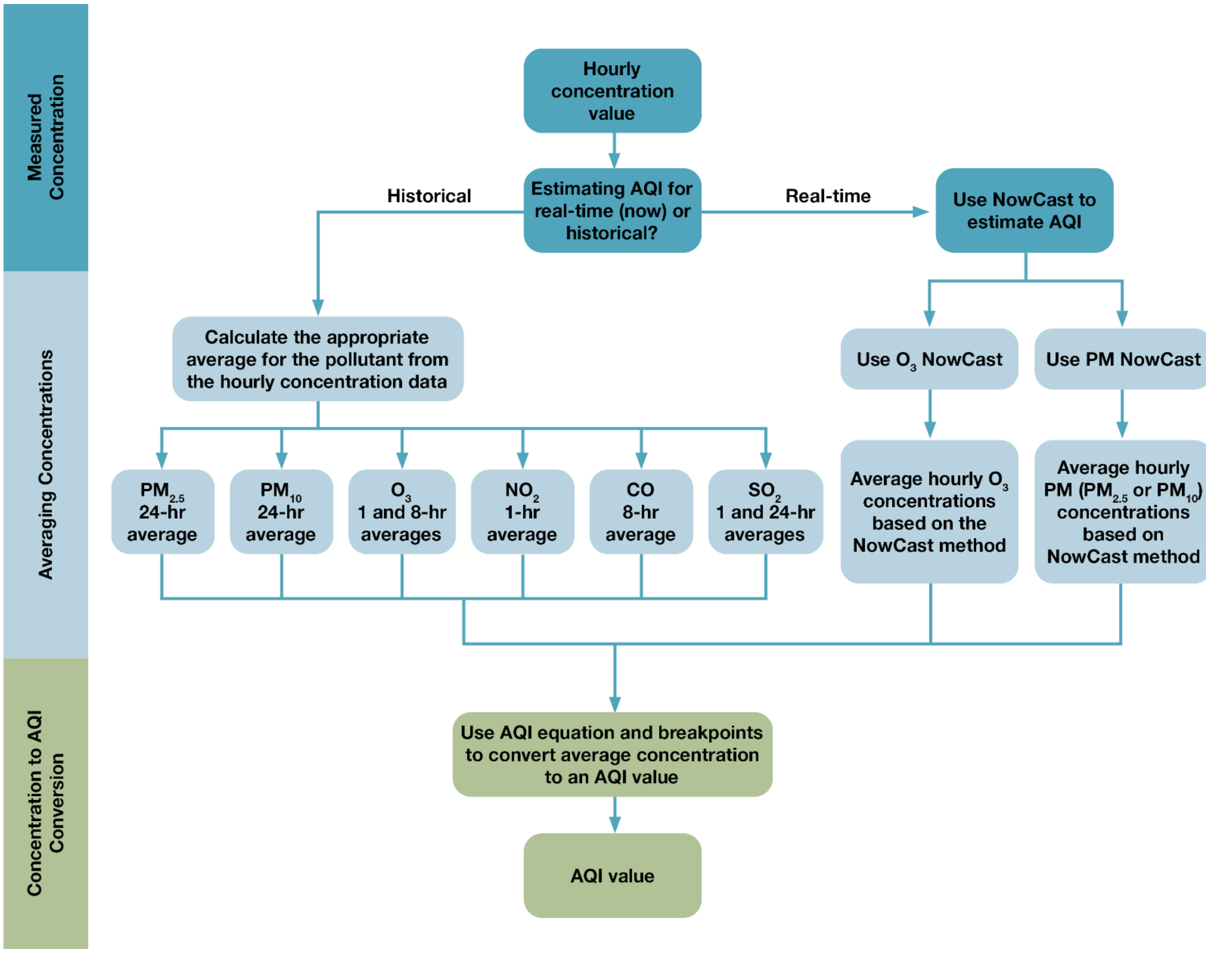


Figure D-4. Flow Chart Showing How to Compute the AQI

There are several important considerations when calculating the AQI using air sensor data:

1. **Sensor data must first be corrected to be more comparable to FRM/FEM reference instruments.** The Clean Air Act requires air quality to be monitored nationally within the U.S., using Federal Reference Method (FRM) or Federal Equivalent Method (FEM) instruments. Sensor data must first be harmonized (discussed above) and corrected (see *Section 3.6.2*) so that the data will be more comparable to the ambient air quality network.

2. **Data is averaged to correspond to the NAAQS.** For historical data (i.e., not real-time), the U.S. EPA calculates the AQI values from air data averages over 1, 8, or 24 hours using the AQI equation (see #3 below). The reason for the different averaging times is that different pollutants affect the human body in different ways as presented in Table 2-2.

Tip: Be aware that reference instrument data is the only data that determines NAAQS compliance

3. **NowCast AQI is used for PM and O_3.** For current air quality conditions, the U.S. EPA calculates the AQI values using a method called NowCast to estimate short-term averages that are then converted using the AQI formula (see below). Note that the NowCast AQI is only calculated for O_3 and PM because these pollutants commonly drive the AQI. The NowCast calculations for PM and O_3 are different as these pollutants behave differently in the atmosphere and have different NAAQS averaging times. For example, the NowCast AQI for PM shows air quality for the most current hour available by using a calculation that involves multiple hours of past data. The NowCast uses longer averages during periods of stable air quality and shorter averages when air quality changes rapidly, such as during a wildfire event.

4. **Online tools are available to calculate the AQI.** Once you have calculated an average concentration, use the following equation to compute the AQI for a given pollutant. An online AQI calculator is available to help with this conversion.

$$AQI = \left[\frac{(AQI_{Hi}) - (AQI_{Lo})}{(Conc_{Hi}) - (Conc_{Lo})} \times (Conc_i) - (Conc_{Lo})\right] + (AQI_{Lo})$$

Where:
$Conc_i$ = Truncated concentration for a given pollutant
$Conc_{Lo}$ = Concentration breakpoint that is less than or equal to $Conc_i$
$Conc_{Hi}$ = Concentration breakpoint that is greater than or equal to $Conc_i$
AQI_{Lo} = AQI value/breakpoint corresponding to $Conc_{Lo}$
AQI_{Hi} = AQI value/breakpoint corresponding to $Conc_{Hi}$

You can find the latest AQI-Concentration breakpoints here and the rules for truncating concentrations are:

O_3 (ppm) – truncate to 3 decimal places
$PM_{2.5}$ (µg/m^3) – truncate to 1 decimal place
PM_{10} (µg/m^3) – truncate to integer
CO (ppm) – truncate to 1 decimal place
SO_2 (ppb) – truncate to integer
NO_2 (ppb) – truncate to integer

For example, using an average $PM_{2.5}$ value of 35.9 µg/m^3 and the $PM_{2.5}$ breakpoints in Table D-1 results in an AQI of 102:

$$\left[\frac{(150) - (101)}{(55.4) - (35.5)} \times (35.9) - (35.5)\right] + (101) = 102$$

Table D-1. Example Breakpoints for $PM_{2.5}$

AQI Category	AQI Color	$PM_{2.5}$ $Conc_{Lo}$ (µg/m^3)	$PM_{2.5}$ $Conc_{Hi}$ (µg/m^3)	AQI_{Lo}	AQI_{Hi}
Good	Green	0.0	12.0	0	50
Moderate	Yellow	12.1	35.4	51	100
Unhealthy For Sensitive Groups	Orange	35.5	55.4	101	150
Unhealthy	Red	55.5	150.4	151	200
Very Unhealthy	Purple	150.5	250.4	201	300
Hazardous	Maroon	250.5	500.4	301	500

Appendix E: Interpreting Sensor Performance Evaluation Results

As mentioned in Section 4.3.1, the U.S. EPA's Targets Reports provide templates to encourage a similar format for reporting sensor evaluation results. This Appendix will walk you through a performance evaluation report for base testing (field evaluation) as this testing is recommended, at a minimum. Using the reporting template as an example, this Appendix will review the types of information that testing organizations are being asked to report, why this information might be important to sensor users, and how sensor users should use and interpret the information provided.

The base testing reporting template for fine particulate matter ($PM_{2.5}$) sensors is shown in Figures E-1, E-2, and E-3. Page 1 (Figure E-1) includes deployment details and several graphs where testers can visually summarize sensor performance. Page 2 (Figure E-2) contains tables for all of the calculated performance metrics and performance statistics. There is also space for additional scatterplots so that a separate graph can be displayed for each evaluated sensor. Page 3 (Figure E-3) includes a table where testers can share what additional documentation is included with the evaluation report that would be helpful for sensor users in interpreting the results. Testers can choose to attach additional information or write a short description of that information in the table.

An example of a filled in reporting template is provided here using results from one of the U.S. EPA's field evaluations of the AirBeam2 sensor compared to the T640x reference instrument. The AirBeam2 is no longer available for purchase and has been chosen for illustration purposes only.

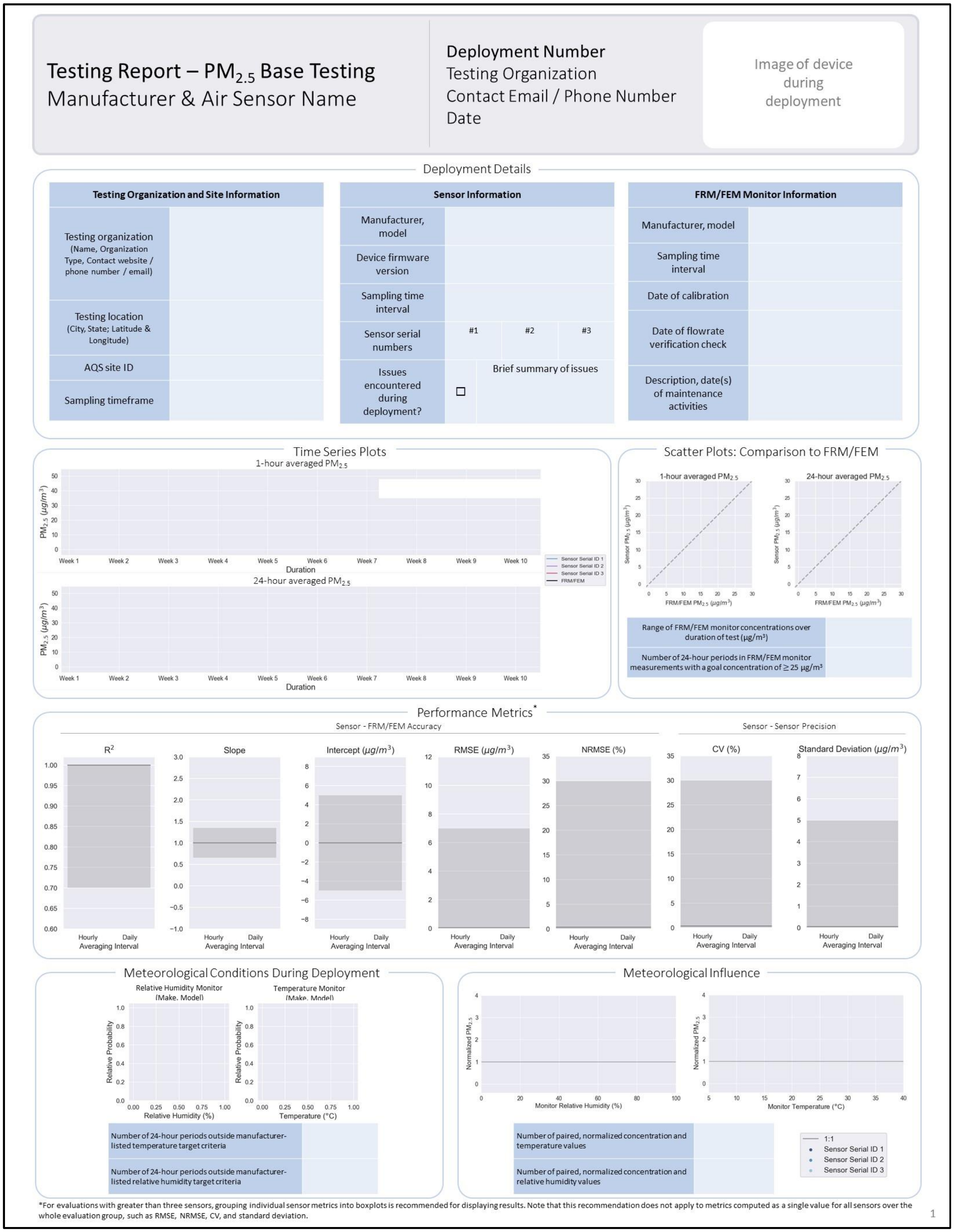


Figure E-1. Page 1 of U.S. EPA's Base Testing Reporting Template for $PM_{2.5}$ Sensors – Deployment Details and Visual Plots of Sensor Performance

Testing Report – $PM_{2.5}$ Base Testing
Manufacturer & Air Sensor Name

Deployment Number
Testing Organization
Contact Email / Phone Number
Date

Image of device during deployment

Tabular Statistics

- Sensor – FRM/FEM Correlation

	Bias and Linearity						Data Quality			
	R^2		Slope		Intercept (b) (μg/m³)		Uptime (%)		Number of paired sensor and FRM/FEM concentration values	
	1-Hour ○○○	24-Hour ○○○	1-Hour ○○○	24-Hour ○○○	1-Hour ○○○	24-Hour ○○○	1-Hour ○○○	24-Hour ○○○	1-Hour	24-Hour
Metric Target Range	≥ 0.70	≥ 0.70	1.0 ± 0.35	1.0 ± 0.35	-5 ≤ b ≤ 5	-5 ≤ b ≤ 5	90%*	90%*		
Sensor Serial #1										
Sensor Serial #2										
Sensor Serial #3										
Mean										

	Error			
	RMSE (μg/m³)		NRMSE (%)	
	1-Hour ○	24-Hour ○	1-Hour ○	24-Hour ○
Metric Target Range	≤ 7	≤ 7	≤ 30	≤ 30
Deployment Value				

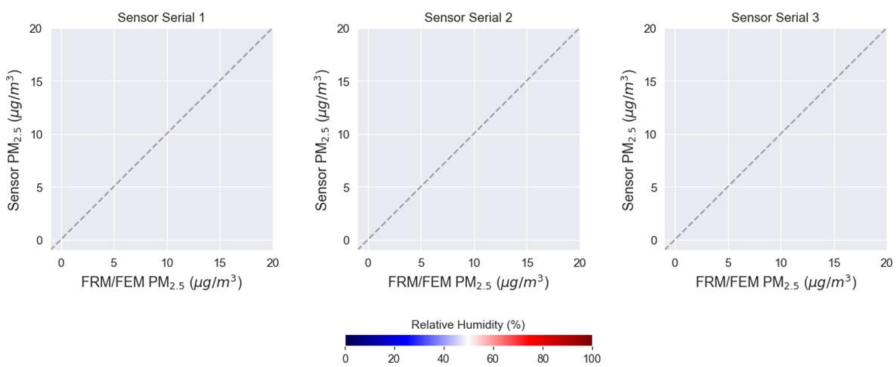
Device-specific metrics (computed for each sensor in evaluation)
○○○ Metric value for none of devices tested falls within the target range
●○○ Metric value for one of devices tested falls within the target range
●●○ Metric value for two of devices tested falls within the target range
●●● Metric value for three of devices tested falls within the target range

Single-valued metrics (computed via entire evaluation dataset)
○ Indicates that the metric value is not within the target range
● Indicates that the metric value is within the target range

- Sensor – Sensor Precision

	Precision (between collocated sensors)				Data Quality			
	CV (%)		SD (μg/m³)		Uptime (%)		Number of concurrently reported sensor concentration values	
	1-Hour ○	24-Hour ○	1-Hour ○	24-Hour ○	1-Hour ○	24-Hour ○	1-Hour	24-Hour
Metric Target Range	≤ 30	≤ 30	≤ 5	≤ 5	90%*	90%*		
Deployment Value								

Individual Sensor – FRM/FEM Scatter Plots



*This value is only a recommendation for ensuring data quality and is not included in the list of target values discussed in Section 4 of the *Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors* document.

2

Figure E-2. Page 2 of U.S. EPA's Base Testing Reporting Template for $PM_{2.5}$ Sensors – Tables and Graphs Summarizing Sensor Performance

Testing Report – $PM_{2.5}$ Base Testing
Manufacturer & Air Sensor Name

Deployment Number
Testing Organization
Contact Email / Phone Number
Date

Image of device during deployment

Supplemental Information

Additional documentation may be attached or linked to digital versions alongside this report. Such documentation may include field reports and observations during the testing period, maintenance logs for sensors and FRM/FEM monitors, standard operating procedures, and other documentation relevant to this testing report (see below for examples).

Supplemental Documentation	Attached	Description & URL or file path to documentation
Field observations	☐	
Maintenance logs	☐	
Standard operating procedure(s)	☐	
Photos of equipment setup and testing	☐	
Product specification sheet(s)	☐	
Product manual(s)	☐	
Deployment issues	☐	
Data storage and transmission method	☐	
Data correction approach	☐	
Data analysis/correction scripts and version	☐	
Air Monitoring Station QAPP	☐	
Summary of FRM/FEM monitor QC checks	☐	
Other documents	☐	

3

Figure E-3. Page 3 of U.S. EPA's Base Testing Reporting Template for $PM_{2.5}$ Sensors – Table Documenting Supplemental Materials and Information

E.1 Deployment Details

In the reporting template, you will find a summary of the testing organization name and type, test site, air sensors, and reference instrument used (see Figures E-1, E-4, E-5, and E-6).

Testing Organization and Site Information. The first box includes the testing organization and site information (Figure E-4) which is designed to give users easy access to information on who conducted the test, and where and when the test was conducted.

Test organization gives users a point of contact if they have questions about the evaluation. Users can view the testing organization name and type (e.g., manufacturer, routine testing facility, government agency, academic institution). This information can give users an idea of the background (e.g., level of experience, objectivity of the tester) and the credentials of the tester.

Testing Organization and Site Information	
Testing organization (Name, Organization type, Contact website)	U.S. Environmental Protection Agency - Office of Research and Development Federal Government Air Sensor Toolbox | U.S. EPA Website
Testing location (City, State, Latitude and Longitude)	Ambient Monitoring Innovative Research Station (AIRS) RTP, NC 35.88951, -78.874572
AQS site ID	37 – 063 – 0099
Sampling timeframe (MM-DD-YY)	06-09-21 to 07-02-21
Sensor data source	weekly downloads from the AirCasting website
Reference data source	OAQPS file transfer

Figure E-4. Testing Organization and Site Information Details of the Reporting Template

Testing location provides the site name, city and state, and latitude/longitude of the testing site. This information may allow users to identify whether the climate at the testing location(s) is similar to where they intend to use sensors. If the test is conducted at an existing air monitoring site within the United States (U.S.), the report may list the U.S. EPA's Air Quality System (AQS) Site ID. This ID is a nine-digit number which uniquely identifies the testing location and helps connect the reference instrument data within the AQS database. For tests conducted in other countries, a similar ID or other identifier may be provided that links the reference data to a database. Keep in mind that an AQS ID may not be available if a testing organization sets up their own test site.

Sampling timeframe lists the start and end date/time of the sensor evaluation. This information may allow users to identify whether the climate conditions during the test is similar to the climate where they intend to use sensors. This information may also help users identify whether climate (e.g., rainy seasons) or seasonal sources (e.g., seasonal dust source, seasonal woodsmoke from home heating) may have impacted the test results.

Sensor data source describes how the sensor data was obtained. For example, data may have been collected from an on-board microSD card or through the manufacturer's cloud server. Some sensors provide multiple ways of obtaining the data and there may be differences within the data files depending on how they were obtained (e.g., different time resolution, data processing method). Documenting the data source makes it easier to access the data source especially in cases where issues are identified later.

Reference data source describes how the reference instrument data was obtained. For example, data may have been transferred directly from an air monitoring agency that collected it, downloaded from AirNow or AirNowTech, or downloaded from AQS. These data sources have unique characteristics. For example, data downloaded from AirNow is collected in real-time and several automated quality control (QC) checks are performed before the data is posted. On the other hand, data downloaded from AQS has undergone more quality assurance (QA) review and is certified quarterly. Therefore, it is possible for the AirNow dataset to contain data that is later flagged as invalid and removed from the AQS database. Documenting the data source makes it easier to access the data and can help explain differences between similar analyses using different data sources.

Sensor Information. The sensor information column (Figure E-5) is designed to give users a quick overview of the sensor equipment tested and if there were any issues with the equipment during the evaluation.

Sensor Information			
Manufacturer, model	HabitatMap AirBeam2		
Device firmware version	Unknown (purchased Nov 2019)		
Sampling time interval	1-minute		
Sensor serial numbers	56C	63B	546
Issues encountered during deployment?	☐	Issues with deployment	

Figure E-5. Sensor Information Details of the Reporting Template

Manufacturer, model applies to commercially available sensors. Testers are asked to list the manufacturer and model of the sensor device. This is important because improvements or changes to the components of the sensor or how those components are configured within a device can impact sensor performance.

Device firmware version is also requested. As mentioned previously, it is extremely important to have a sense of how the data are processed from the raw sensor output into pollutant concentrations. This may happen on the device itself or within a manufacturer's cloud-based data platform. Since manufacturers may change the processing of data on-board, it is important that a performance evaluation includes the configuration and data processing details. Testers can share supplemental information on the firmware and data processing at the end of the reporting template.

Sampling time interval varies among sensors. Many sensors on the market provide data very quickly (e.g., a new data point every minute). Some devices produce data at a steady time interval (i.e., consistently every minute exactly on the minute) while others do not. The sampling time interval box shows how often the sensor produces data. Whatever the sampling time interval is, the data can be averaged to produce longer time averages.

Sensor serial numbers capture the unique IDs for each device tested. EPA's Targets Reports recommend testing at least 3 sensor devices simultaneously. This approach allows users to better understand how sensor performance varies among identical sensors. Recording the serial numbers helps testers connect the data files with the sensor device being tested. For sensors that have remote data viewing platforms, manufacturers often track the data and sensor configuration by the serial number. This is also useful information for users when viewing graphs of the data or identifying which sensors had issues during the testing.

Issues encountered during deployment allows testers to record any problems during the testing. It is possible for something to go wrong during testing (e.g., sensor loses power, a wasp makes a nest inside the sensor affecting result). If there were issues, testers can indicate these by checking the box on the left. Additional information on these issues can be described in more detail in the supplemental information section in the reporting template.

FRM/FEM Information. The FRM/FEM information column (Figure E-6) is designed to give users a quick overview of the reference instruments used during testing.

Manufacturer and model of the reference instrument can be used to confirm that the instrument has been designated as a FRM/FEM by the U.S. EPA. The manufacturer's website provides details on how the pollutant concentration measurement is made. This may help users in interpreting similarities or differences in testing results if the same sensor device was tested with a different FRM/FEM monitor.

FRM/FEM Information	
Manufacturer, model, designation	Teledyne Advanced Pollution Instrumentation T640x FEM
Sampling time interval	1-hour averaging
Date of calibration	As required by 40 CFR Part 58 and the Burdens Creek QAPP maintained by OAQPS
Date of flowrate verification check	Monthly as required by 40 CFR Part 58 Appendix A
Description, date(s) of maintenance activities	No maintenance activities recorded during testing

Figure E-6. FRM/FEM Information Details of the Reporting Template

Sampling time interval shows how often the FRM/FEM monitor produces data. Reference instruments for some pollutants may return data quickly (e.g., every minute) while monitors for other pollutants may return data less frequently (e.g., every hour).

Date of calibration, date of flowrate verification check, and description, dates of maintenance activities captures information on routine quality control (QC) procedures. To maintain proper operation and high data quality, FRM and FEM monitors undergo routine QC procedures such as calibration checks, flowrate checks, and regular maintenance. If the regular schedule of maintenance and checks is ignored, data quality can suffer. These activities are conducted routinely at existing air monitoring sites within the U.S. but may not be as routine in other locations or at temporary sites set up for a limited number of evaluations. While this section is designed to capture a snapshot of information, testers can provide additional information in the supplemental section of the reporting template or by citing an approved site monitoring plan and checklist.

How Do I Find Which Instruments are Designated as FRM/FEM Monitors?

Instruments designated as FRM/FEM monitors can be found on U.S. EPA's Ambient Monitoring Technology Information Center (AMTIC) on the following webpage: https://www.epa.gov/amtic/air-monitoring-methods-criteria-pollutants

The list of FRM/FEM monitors is typically updated twice a year.

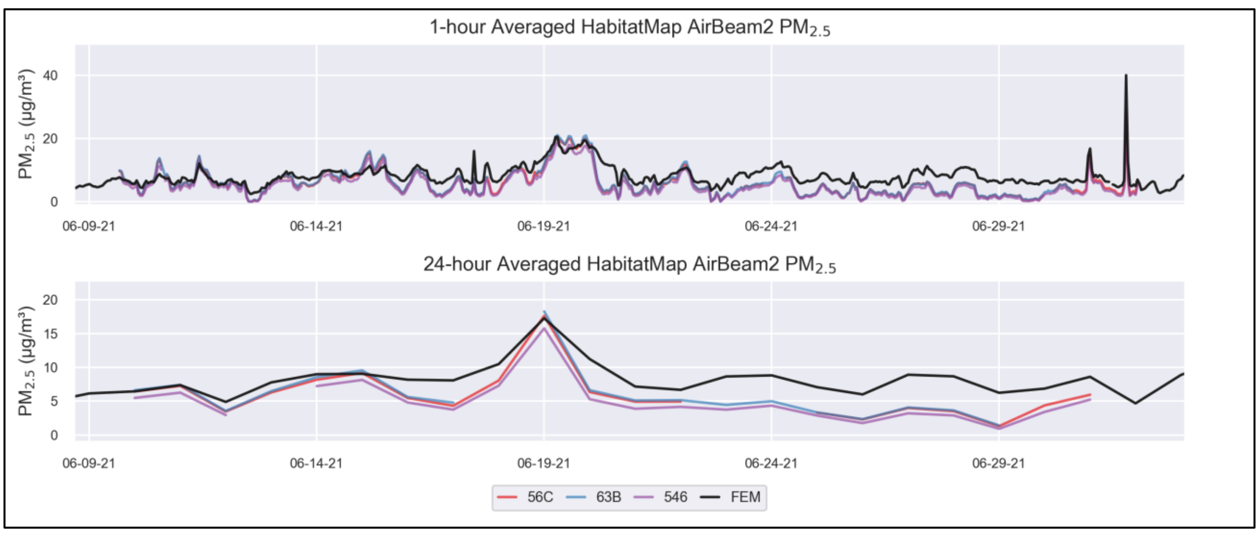


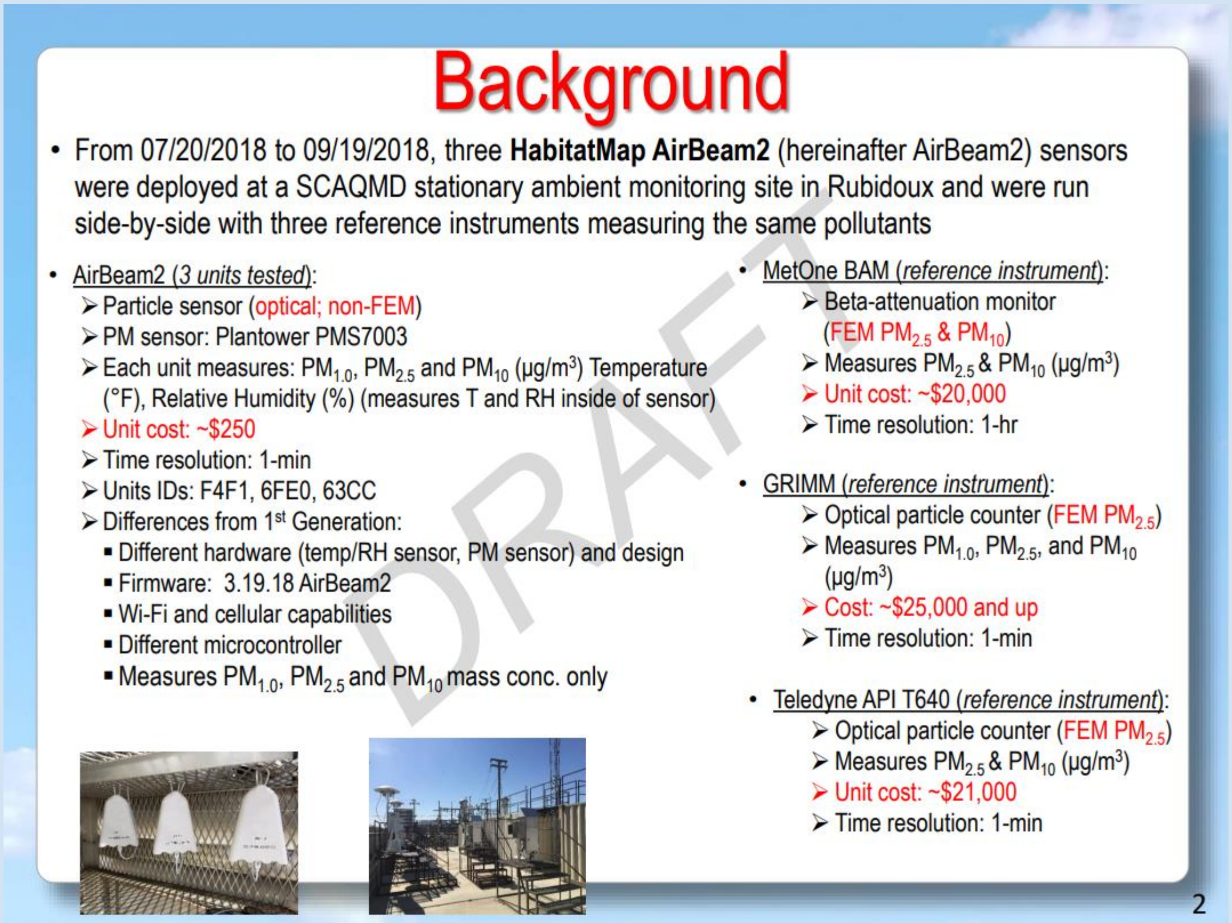
Figure E-7. Time Series Plots in the Reporting Template

E.2 Time Series Plots

The Targets Reports ask testers to create a time series plot (see example in Figure E-7) which shows the data from each of the three identical sensors alongside data from the reference monitor as a function of time. The purple, blue, and red lines represent the sensors and the black line represents the reference monitor. Some reports, like the example in Figure E-7, may include more than one plot, showing data at different averaging intervals (e.g., 1-hour, 8-hour, 24-hour). All averages should represent the time period they describe. A data completeness level of at least 75% is recommended when calculating these averages (see Section 3.7.2 and Table 3-2). Testers are asked to share how they calculate data averages if they do not follow the recommendation in the Targets Reports.

Do other Testing Organizations Provide Details on the Instruments Evaluated and Testing Conditions in their Evaluation Reports?

Yes! Most testing organizations document these details, but they may not be presented all in one place. Some details may be held in private files, within longer reports, or within various locations in a testing report. Here is one example report from AQ-SPEC where similar information is presented within a draft field evaluation report.

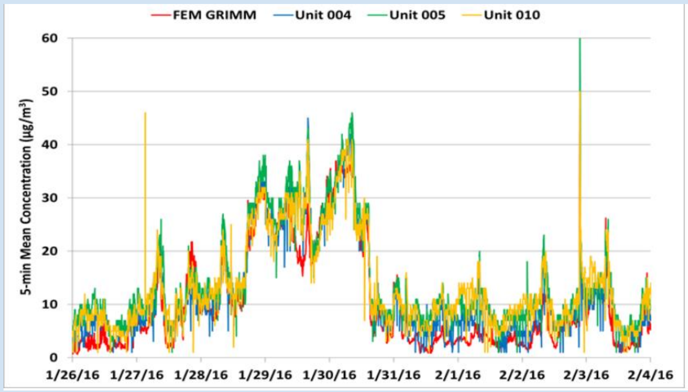


The primary purpose of the time series plot(s) is to show how measurements change over time. These plots help users determine if the sensors capture the same variation in measurements (trends) as the reference monitor over the testing period. If some time periods show poor agreement, users should review the supplemental information in the reporting template to understand if there were any issues during those time periods that may have influenced sensor performance.

The time series plots may also give users insight into whether sensors over- or under-estimate pollutant concentrations. When sensor measurements are lower than the reference instrument measurements, that is referred to as **underestimating** concentrations. When sensor measurements are higher than the reference monitor measurements, that is referred to as **overestimating** concentrations. Some sensors may show a combination of underestimating and overestimating concentrations.

Are All Time Series Plots Similar?

Yes and no. Time series plots always show time along the horizontal x-axis and pollutant concentration along the vertical y-axis. There may be differences in the colors used, time averaging interval, and number of sensors plotted. The image example below show an example from an AQ-SPEC report. Occasionally you might also see a secondary vertical y-axis if pollutant concentrations are reported in different units or if multiple pollutants are plotted on one graph.



Lastly, the time series plots may show **data spikes**, or data points with higher concentrations, from one or more of the instruments. Users may want to pay close attention to these spikes. Some spikes may represent elevated pollutant concentrations outdoors. For example, particulate matter (PM) concentrations may go up for a short period of time because of nearby mowing activities. Other spikes may not reflect real changes in pollutant concentrations and may instead indicate that something is wrong with the device. Past sensor evaluation efforts have found several sensors that report false information occasionally as a result of incorrectly logged data or a device error. Users should check the supplemental information in the testing report to identify if any of the data spikes were removed from the dataset. If this information is not available, users should contact the testing organization.

E.3 Scatter Plots

The next part of the reporting template asks testers to create a scatter plot (see example in Figure E-8) which graphs data from the sensors against data from the reference monitor. In Figure E-8, 1-hour or 24-hour averaged data are shown. The Targets Reports recommend making this plot with the sensor data on the y-axis and the reference data on the x-axis. Other testing organizations may plot the data differently so be careful to note which axis the data is plotted on when interpreting these plots. The scatter plot includes the slope-intercept line calculated using the ordinary least-squares regression equation (see Section 3.6.2). As a reminder, the slope and intercept describe the **bias** in the sensor data. If the slope is greater than 1, this means that the sensor measurements are higher than reference instrument measurements (i.e., the sensor **overestimates** concentrations). If the slope is less than 1, this means that the sensor measurements are lower than the reference measurements (i.e., the sensor **underestimates** concentrations)

In the reporting template, testers are asked to include the scatter plot for one of the three sensors against the reference instrument data. Testers are encouraged to include plots for each individual sensor in the supplemental information in the reporting template. Users should check this information to understand how the other identical sensors compared to the reference instrument.

The data points in some scatter plots may have different colors that represent another parameter [e.g., temperature (T), relative humidity (RH)]. The purpose for this is to give users more insight into data. The legend should describe what the colors represent. For example, RH is known to affect the performance of some fine particulate matter ($PM_{2.5}$) sensors. In Figure E-8, the data points in the scatter plot have different colors based on the RH levels (red points represent higher RH levels and blue points represent lower RH levels). If RH affects the performance of a sensor, users may see red dots in one area and blue dots in another.

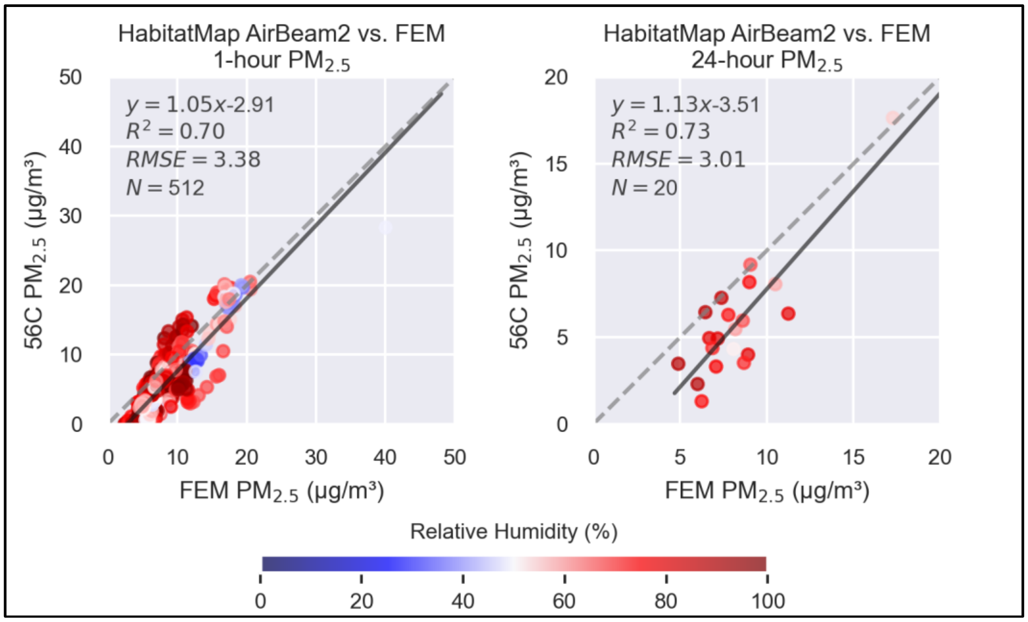


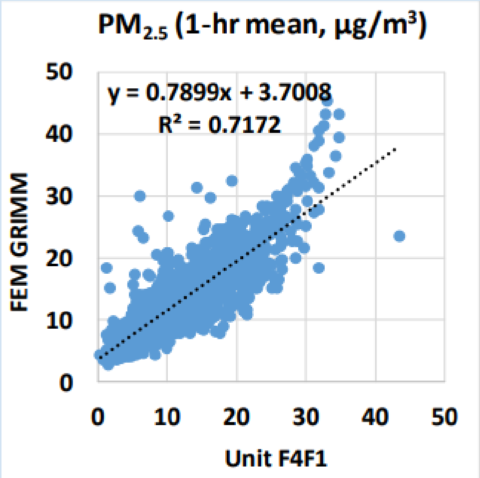
Figure E-8. Scatter Plot in the Reporting Template

Some scatter plots, like those shown in Figure E-8, may include more details or statistics about the data that is plotted. For example, the plot includes the number of data points (N) plotted, and the root mean square error (RMSE), which is a measure of error in the sensor measurements.

Although this scatter plot uses a linear regression to describe the relationship between the sensor and reference data, some sensors or pollutant types may need more complicated function such as a multilinear regression to describe the relationship. A multilinear regression includes two or more variables to predict the outcome of another variable.

Do Some Testing Organizations Choose to Make Scatterplots Differently?

Yes. The recommendations provided by the U.S. EPA are voluntary and testing organizations may choose to plot data differently. Some have chosen to plot reference data on the y-axis and sensor data on the x-axis instead. For example, the plot below is from a draft field evaluation conducted by AQ-SPEC from 2020. This makes the bias interpretation different. More explicitly, because the axes are switched, a slope less than 1 means that the sensor is overestimating concentrations. For simplicity, users can pick a point on the graph and use the x and y coordinates to determine if the sensor reads higher or lower than the reference measurement.



E.4 Performance Evaluation Metrics and Target Values

The Targets Report ask testers to plot the calculated performance metrics (see Figure E-9). A series of plots are included which have dark gray shaded regions that indicate the target value ranged. The plots can help users quickly identify whether a sensor meets the target value for each metric, how close the sensor is to meeting the target value (if the target is not met), and the total number of target values that the sensor meets.

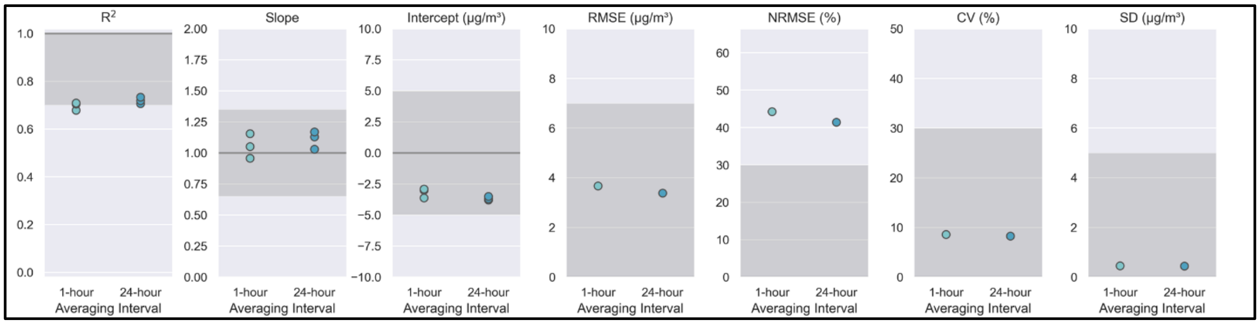
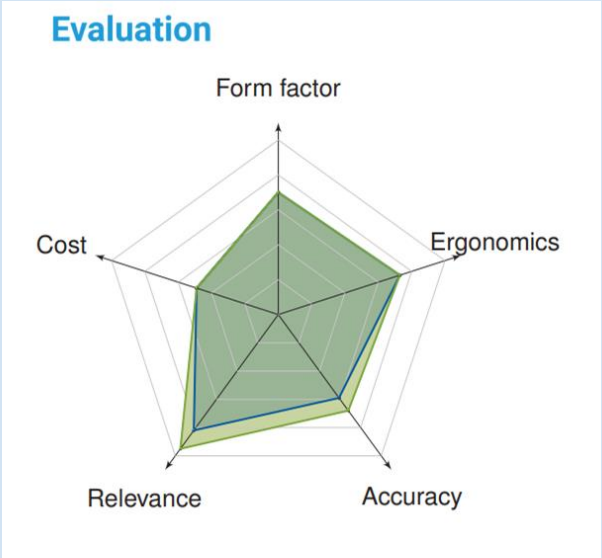


Figure E-9. Performance Metrics in the Reporting Template

When viewing this figure, dots in the light gray space indicate that the sensor does not meet the target whereas dots in the dark gray space indicate that the sensor meets the target. The numerical values for each performance metric are also shown in a table on the second page of the report (see Figure E-10). Target values are included again within the table for easy reference.

Do All Evaluations Use the Same Performance Metrics and Target Values?

No. U.S. EPA's Targets Reports list specific performance metrics, give detailed calculations for each metric, and include target values for those metrics. Testers using other protocols developed by other organizations may report different performance metrics. As an example, the image below shows a report from AIRLAB which uses different metrics and visualizations. If needed, users should ask the testing organization to explain the performance metric calculations and interpretation of results.



Tabular Statistics

Sensor-FRM/FEM Correlation

	Bias and Linearity						Data Quality			
	R²		Slope		Intercept (µg/m³)		Uptime (%)		Number of paired sensor and FRM/FEM concentration values	
	1-Hour ●●○	24-Hour ●●●	1-Hour ●●●	24-Hour ●●●	1-Hour ●●●	24-Hour ●●●	1-Hour ●●●	24-Hour ●●●	1-Hour	24-Hour
Metric Target Range	≥ 0.70	≥ 0.70	1.0 ± 0.35	1.0 ± 0.35	-5 ≤ b ≤ 5	-5 ≤ b ≤ 5	75%*	75%*	-	-
Sensor 56C	0.70	0.73	1.05	1.13	-2.91	-3.51	95	87	512	20
Sensor 63B	0.68	0.71	1.15	1.17	-3.63	-3.80	90	83	485	19
Sensor 546	0.71	0.72	0.96	1.03	-3.01	-3.69	96	91	515	21
Mean	0.70	0.72	1.05	1.11	-3.18	-3.66	93	87	504	20

	Error			
	RMSE (µg/m³)		NRMSE (%)	
	1-Hour ★	24-Hour ★	1-Hour ☆	24-Hour ☆
Metric Target Range	≤ 7.0	≤ 7.0	≤ 30.0	≤ 30.0
Deployment Value	3.7	3.4	44.3	41.5

Device-specific metrics (computed for each sensor in evaluation)
○○○ Metric value for none of devices tested falls within the target range
●○○ Metric value for one of devices tested falls within the target range
●●○ Metric value for two of devices tested falls within the target range
●●● Metric value for three of devices tested falls within the target range

Single-valued metrics (computed via entire evaluation dataset)
☆ Indicates that the metric value is not within the target range
★ Indicates that the metric value is within the target range

Sensor-Sensor Precision

	Precision (between collocated sensors)				Data Quality	
	CV (%)		SD (µg/m³)		Number of concurrent sensor concentration pairs	
	1-Hour ★	24-Hour ★	1-Hour ★	24-Hour ★	1-Hour	24-Hour
Metric Target Range	≤ 30.0	≤ 30.0	≤ 5.0	≤ 5.0	-	-
Deployment Value	8.6	8.3	0.5	0.4	492	19

Figure E-10. Tabular Summary of Sensor Performance Metrics on Page 2 of the Reporting Template

E.5 Meteorological Conditions During the Evaluation

The Targets Reports ask testers to create plots describing the meteorological conditions during the testing period (see example in Figure E-11). The relative probability graphs describe how much data was collected in each T or RH range over the course of the testing period.

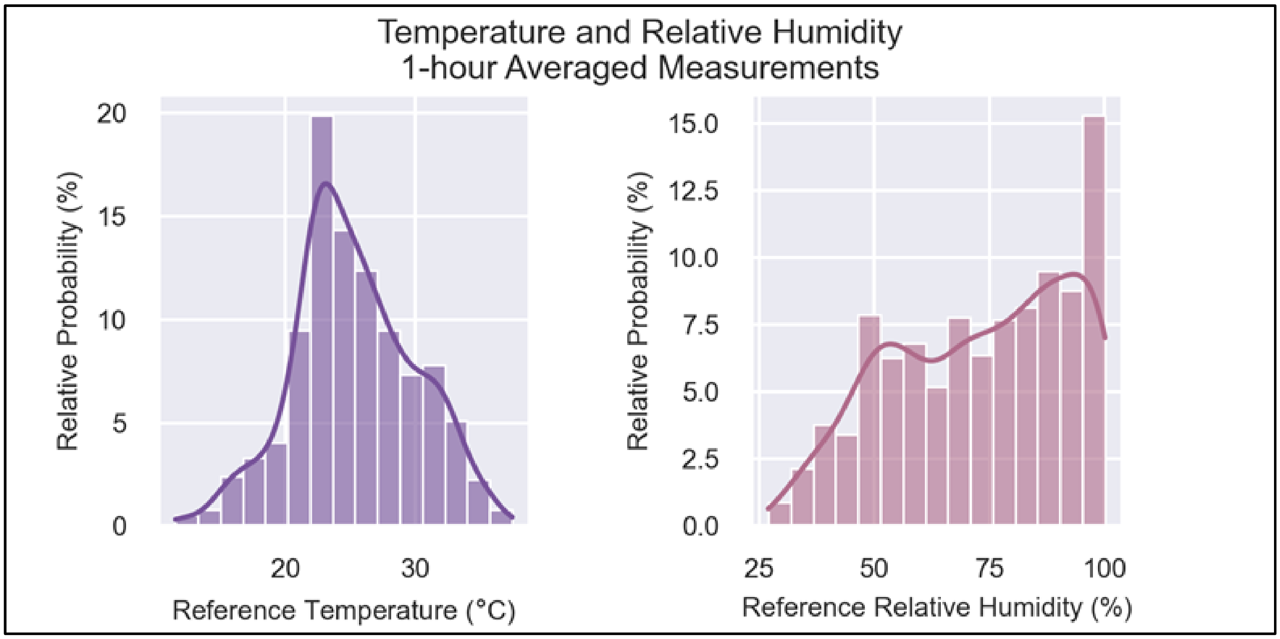


Figure E-11. Meteorological Conditions in the Reporting Template

These graphs can help users understand how similar or different the RH and T evaluation conditions were compared to where they would like to use the sensor. Users should keep in mind that if the meteorological conditions are very different, sensors may perform differently.

Evaluation reports may have additional graphs that show how meteorology impacts sensor performance. The graphs may vary based on the sensor and/or pollutant type.

Appendix F: Glossary

A – B – C – D – E – F – G – H – I – J – K – L – M – N – O – P – Q – R – S – T – U – V – W – X – Y – Z

-A-

accuracy:

A measure of the agreement between the pollutant concentrations reported by the sensor and the reference instrument. This includes a combination of random error (precision) and systematic error (bias) components which are due to sampling and analytical operations. One way to measure this agreement is by calculating the root mean square error. See *Section 3.4.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

aerosol:

Solid or liquid droplets suspended in air originating from biogenic sources (e.g., sea salt spray, volcanoes) and from anthropogenic sources (e.g., fossil fuel combustion, biomass burning). Aerosols can also form in the atmosphere from reactions of chemical precursors (e.g., reaction of ammonia, sulfur dioxide, and water vapor to form ammonium sulfate). See *Section 2.3*.

Source: https://earthobservatory.nasa.gov/features/Aerosols

air quality:

A relative measure of the amount of pollution present in the air. Good air quality means less air pollution, while poor air quality means more air pollution. See *Section 2.1*.

Source: https://www3.epa.gov/airquality/cleanair.html

Air Quality Index (AQI):

U.S. EPA's index for reporting daily air quality that characterizes air pollution levels and associated health effects that might be of concern. EPA calculates the AQI for five criteria pollutants. AQI values range from 0 to 500; the higher the AQI value, the greater the level of air pollution and the greater the health concern. AQI values at or below 100 are generally thought of as satisfactory. When AQI values are above 100, air quality is unhealthy: at first for certain sensitive groups of people, then for everyone as AQI values get higher. See *Sections 2.4 and 2.5*.

Source: https://www.airnow.gov/aqi/aqi-basics/

Air Quality System (AQS):

An electronic repository of ambient air pollution data collected by the U.S. EPA, state, local, and tribal air pollution control agencies from over thousands of monitors The AQS also contains meteorological data, descriptive information about each monitoring station (including its geographic location and its operator), and data quality assurance/quality control information. See *Section 2.3*.

Source: https://www.epa.gov/aqs

air sensor:

A class of non-regulatory technology that is lower in cost, portable, and generally easier to operate than regulatory monitors. Air sensors often provide relatively quick or instant air pollutant concentrations (both gas-based and particulate matter) and allow air quality to be measured in more locations. The term ‘air sensor’ often describes an integrated set of hardware and software that uses one or more sensing elements (also sometimes called sensors) to detect or measure pollutant concentrations. See *Section 1.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

air toxics:

See *hazardous air pollutants*.

anthropogenic emissions:

Emissions that originate from human activities or result from natural processes that have been affected by human activities (e.g., fuel combustion, solvent use, biomass burning). See *Section 2.1*.

Source: https://www.epa.gov/sites/production/files/2021-02/documents/us-ghg-inventory-2021-main-text.pdf

-B-

benzene, toluene, ethylbenzene, and xylene (BTEX):

Mixture of four volatile organic compounds (benzene, toluene, ethylbenzene, and xylene) that are normally grouped as they are often found together. Primary sources of BTEX include on-road and non-road gasoline vehicles and engines, petroleum transport/storage, and solvent usage. See *Section 2.1*.

Source: https://mde.maryland.gov/programs/LAND/OilControl/Documents/BTEX%20Fact%20Sheet%202.12.07%202%20pgs.pdf

bias:

The systematic (non-random) or persistent disagreement between the concentrations reported by the sensor and reference instrument. It is often determined using the linear regression slope and intercept of a simple linear regression, fitting sensor measurements (y-axis) to reference measurements (x-axis). See *Section 3.4.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

biogenic emissions:

Air emissions that originate from a natural source such as vegetation, soils, volcanic emissions, lightning, sea salt, etc. Also called *natural sources*. See *Section 2.1*.

Source: https://www.epa.gov/air-emissions-modeling/biogenic-emission-sources

black carbon (BC):

Most strongly light-absorbing component of particulate matter (PM) that is formed by the incomplete combustion of fossil fuels, biofuels, and biomass. BC is emitted directly into the atmosphere in the form of fine particulate matter ($PM_{2.5}$). BC is the most effective form of PM, by mass, at absorbing solar energy – per unit of mass in the atmosphere, BC can absorb a million times more energy than carbon dioxide (CO_2). BC is a major component of “soot”, a complex light-absorbing mixture that also contains some organic carbon (OC). See *Section 2.1*.

Source: https://www3.epa.gov/airquality/blackcarbon/basic.html

-C-

calibration:

A procedure for checking and adjusting an instrument's settings so that the measurements produced are comparable to a certified standard value. See *Section 3.6*.

Source: https://www3.epa.gov/ttnamti1/files/ambient/pm25/qa/vol2sec12.pdf

certification:

A process where an organization carries out an agreed upon test method(s) set by standards to make sure tests are conducted in the same way every time. The certification process often results in a certificate or specific label [e.g., ENERGY STAR label, Underwriter Laboratories (UL) listing)]. See *Section 4.3.1*.

citizen science:

See *participatory science*.

Code of Federal Regulations (CFR):

The codification of the general and permanent rules published in the Federal Register (a daily publication of the U.S. Federal Government that issues proposed and final administrative regulations of federal agencies) by the executive departments and agencies of the U.S. Federal Government. CFR is divided into 50 titles that represent broad areas subject to Federal regulation, and each title is divided into chapters typically bearing the name of the issuing agency. Each chapter is further subdivided into parts (and subparts, where needed) that cover specific regulatory areas. See *Section 2.3*.

Source: https://www.archives.gov/federal-register/cfr/about.html

collocation:

The process by which a sensor and a reference instrument are operated at the same time and place under real world conditions. The siting criteria (e.g., proximity and height of the sensor and the reference monitor) should follow procedures outlined in 40 CFR Part 58 as closely as possible. For example, sensors should be placed within 20 meters horizontal of the reference instrument, positioned such that the sample air inlets for the sensors are within a height of ± 1 meter vertically of the sample air inlets of the reference instrument, and placed as far as possible from any obstructions (e.g., trees, walls) to minimize spatial and wind turbulence effects on sample collection. See *Section 3.6*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

community science:

See *participatory science*.

comparability:

The level of overall agreement between two separate data sets. This term is often used to describe how well sensor data compares with reference instrument data. Comparability is a combination of accuracy, precision, linearity, and other performance metrics. See *Section 3.4.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

completeness:

In determining averages, completeness describes the amount of valid data obtained relative to the averaging period. The purpose of the completeness threshold is to make sure that the average is representative of the concentrations observed within the averaging period. For example, if a sensor collects measurements every 5 minutes, it can return 12 measurements every hour. To obtain 75 percent data completeness for a calculated hourly average, at least 9 valid measurements are needed (i.e., 9/12 * 100 percent = 75 percent). See *Section 3.7.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

concentration:

The metric for reporting the amount of a pollutant in the air. Concentration represents the weight or number of molecules in a volume of air. Common units include microgram per cubic meter (µg/m3), parts per million (ppm), and parts per billion (ppb). For example, a concentration of 43 µg/m3 is the weight of 43 micrograms (a microgram is one millionth of a gram) per cubic meter of air. Parts per billion is the number of units of mass of a pollutant per 1 billion units of the total mass of the air. See *Section 2.1*.

Source: https://en.wikipedia.org/wiki/Air_pollutant_concentrations

correction:

The adjustments to sensor measurement data to more closely match the measurement data collected by a reference monitor. See *Section 3.6*.

criteria pollutant:

A group of six widespread and common air pollutants for which EPA established National Ambient Air Quality Standards (NAAQS) under the Clean Air Act. The criteria pollutants include carbon monoxide (CO), lead (Pb), ground-level ozone (O_3), nitrogen dioxide (NO_2), particulate matter ($PM_{2.5}$ and PM_{10}), and sulfur dioxide (SO_2). See *Section 2.3*.

Source: https://www.epa.gov/criteria-air-pollutants

cross-sensitivity:

Other pollutants that interfere with the measurement of the target pollutant. See *Section 3.7.2*.

-D-

data aggregation:

The process of compiling information to prepare combined datasets for data processing. See *Appendix D*.

data dictionary:

Detailed description of names and definitions of parameters collected in a database. See *Section 3.8.2*.

data handling:

The process of collecting, storing, processing, and presenting or reporting data. See *Section 3.4.2*.

data management system (DMS):

A collection of procedures and software needed to acquire, process, and distribute data. See *Section 3.7.3*.

data quality objectives (DQO):

Quantitative acceptance criteria for the quality and quantity of data to be collected, relative to the ultimate use of the data. See *Section 3.3*.

Source: https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

data spikes:

Data points with higher concentrations from one or more instruments. See *Section 3.6.2*.

data transmission:

Sending or receiving data using a wireless or cable-based relay system. See *Section 3.4.1*.

data validation:

A pollutant- and sample-specific process that extends the evaluation of data beyond method, procedural, or contractual compliance (i.e., data verification) to determine the analytical quality of a specific data set. See *Section 3.7.2*.

Source: https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

deployment:

The placement or arrangement of air sensors or instruments for a specific monitoring purpose or objective. See *Section 3.5*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

detection limit:

The lowest concentration that can be determined as being above zero by a single measurement at a stated level of certainty. There are many types of detection limits, such as the Method Detection Limit (MDL) which is typically defined as 99% confidence that the measurement is not instrument noise. See *Section 3.4.1*.

Source: https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

detection range:

The lowest and highest pollutant concentration that an air sensor can reliably measure. Also called measurement range. See *Section 3.4.1*.

downtime:

The period of time for which an air sensor or instrument is unavailable for use (e.g., during power interruption or maintenance). See *Section 3.7.2*.

downwind:

Where air goes after moving over an area of interest. See *Section 2.1*.

Source: https://www.epa.gov/interstate-air-pollution-transport/what-interstate-air-pollution-transport

drift:

A change in the response or concentration reported by a sensor when challenged by the same pollutant concentration over a period during which the sensor is operated continuously and without adjustment. See *Section 3.7.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

-E-

electrochemical sensor:

A type of air sensor where the target gas interacts with an electrode thereby producing an electrical current that is proportional to the concentration of the target gas. See *Section 3.7.2*.

Source: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100F2G5.PDF?Dockey=P100F2G5.PDF

error:

A measure of the disagreement between the pollutant concentrations reported by the sensor and the reference instrument. One way to measure error is by calculating the root mean square error (RMSE). Additional ways include calculating the mean bias error (MBE), mean absolute error (MAE), among others. See *Section 3.4.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

exposure:

Contact of a chemical, physical, or biological agent (e.g., ozone) with the outer boundary of an organism. Exposure is quantified as the concentration of the agent in the medium in contact integrated over the time duration of that contact. See *Section 2.5*.

Source: https://www.epa.gov/sites/production/files/2014-11/documents/guidelines_exp_assessment.pdf

exceedance:

Occurs when a measured concentration of a criteria pollutant exceeds the concentration level for the averaging period specified by the National Ambient Air Quality Standards (NAAQS). A NAAQS exceedance does not constitute a NAAQS violation. See *Section 2.4*.

-F-

Federal Equivalent Method (FEM):

A method for measuring the concentration of an air pollutant in the ambient air that has been designated as an equivalent method in accordance with 40 CFR Part 53. A FEM does not include a method for which an equivalent method designation has been canceled in accordance with 40 CFR Parts 53.11 or 53.16. See *Section 2.3*.

Source: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-53

Federal Reference Method (FRM):

A method of sampling and analyzing the ambient air for an air pollutant that is specified as a reference method in 40 CFR Part 50, or a method that has been designated as a reference method in accordance with 40 CFR Part 53. A FRM does not include a method for which the U.S. EPA has cancelled a reference method designation in accordance with 40 CFR Parts 53.11 or 53.16. See *Section 2.3*.

Source: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-53

fine particulate matter ($PM_{2.5}$):

See *$PM_{2.5}$*.

firmware:

A type of computer software or set of instructions programmed on a hardware device (e.g., an air sensor). See *Section 3.7.3*.

Source:
https://www.techopedia.com/definition/2137/firmware#:~:text=Firmware%20is%20a%20type%20of,tasks%20and%20functions%20as%20intended

-H-

hotspot:

An area of localized, increased pollutant concentrations (e.g., a congested roadway intersection). See *Section 3.2*.

Source: https://www.greenfacts.org/glossary/abc/air-pollution-hot-spot.htm

hazardous air pollutants (HAPs):

Also called *air toxics*. Air pollutants that are known or expected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental and ecological effects. Examples of toxic air pollutants include benzene (found in gasoline), perchloroethylene (emitted from some dry-cleaning facilities), and methylene chloride (used as a solvent by a number of industries). Example of other listed air toxics include dioxin, asbestos, toluene, and metals such as cadmium, mercury, chromium, and lead compounds. See *Section 2.3*.

Source: https://www.epa.gov/haps

hyperlocal emissions source:

An emissions source that releases brief, but high pollutant concentrations that can influence the air quality of nearby locations but are not representative of the larger area. See *Section 3.5.2*.

Source: https://www.epa.gov/air-sensor-toolbox/guide-siting-and-installing-air-sensors

-I-

interferent:

Any non-target pollutant(s) that might skew or influence a sensor's response to the target pollutant. Interferents may have a positive or negative effect on a sensor signal. See *Section 3.7.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

-L-

linear regression:

Also called *simple linear regression* or *least-squares regression*. A common statistical approach that models the relationship between one variable as a function of another variable. Linear regression estimates the equation: y = mx + b (where "b" is the y-intercept and "m" is the slope) by finding values for the parameters for "b" and "m" that minimize the sum of the squared deviations between the observed responses and the linear equation. See *Section 3.6.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

linearity:

A measure of the extent to which the measurements reported by a sensor can explain the concentrations reported by the reference instrument. It is often quantified by the coefficient of determination (R^2) obtained from the simple linear regression fitting sensor measurements (y-axis) to reference instrument measurements (x-axis) with values closer to 1 generally indicating better linearity. In some cases, sensor measurements can be linear with a near perfect R^2 but may differ significantly from the reference instrument measurements. For example, a linear regression can result in an R^2 of 0.99 and slope of 5. This indicates that the reported sensor measurement is always 5 times higher than the reference instrument measurements. See *Section 3.6.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

long-term:

A time period covering months to years. See *Section 2.2*.

-M-

maintenance:

Preventative actions taken to maintain sensor performance and deployment site conditions over the measurement period. Maintenance can include regularly cleaning of internal surfaces to prevent the buildup of bugs or dust, replacing filters, and examining site conditions for any changes (e.g., vandalism or overgrown trees). Manufacturers may also provide air sensor maintenance activities. See *Section 3.7.1*.

measurement frequency:

The number of measurements collected per unit of time. See *Section 2.3*.

Source: https://www.epa.gov/air-emissions-monitoring-knowledge-base/basic-information-about-air-emissions-monitoring

micrometer:

One millionth of a meter. See *Section 2.1*.

multilinear regression

A statistical approach that describes the relationship among two (2) or more variables to predict the outcome of another variable. See *Appendix E*.

-N-

National Ambient Air Quality Standards (NAAQS):

Standards established by the U.S. EPA that apply to outdoor air throughout the United States. The Clean Air Act (CAA) establishes two types of NAAQS. Primary standards set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards set limits to protect public welfare, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings. EPA has set NAAQS for the six criteria pollutants. See *Section 2.4*.

Source: https://epa.gov/naaqs

near-reference instrument:

An instrument that does not have a Federal Equivalent Method (FEM) designation but has many of the features of an FEM, and when operated by trained staff, can provide air pollution data with sufficient accuracy and quality. See *Section 2.3*.

non-regulatory supplemental and informational monitoring (NSIM):

A term used by the U.S. EPA that describes monitoring applications conducted for purposes other than demonstrating compliance with local, state, or federal air quality regulations. There are three NSIM categories including spatiotemporal variability (e.g., daily trends, gradient studies, air quality forecasting, participatory science, education), comparison (e.g., hotspot detection, data fusion, emergency response, supplemental monitoring), and long-term trend (e.g., long-term changes, epidemiological studies, model verification). See *Section 1.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

-O-

optical technology:

A type of technology used in some particulate matter air sensors. A light receptor detects light scattered by particles and the amount of light scattering (or absorption) is converted into particle count and mass concentration values. See *Section 3.7.2*.

Source: http://www.aqmd.gov/aq-spec/resources/operational-principles

overestimate:

Sensor measurements are higher than the reference instrument measurements. Also called *over-report*. See *Section 3.6.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

-P-

parameter:

Any of a set of physical properties whose values determine the characteristics or operation of an air sensor or instrument. See *Section 3.4.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

participatory science:

Activity that engages the public in advancing scientific knowledge by formulating research questions, collecting data, and interpreting results. Other terms include citizen science, community science, volunteer monitoring, or public participation in scientific research. See *Section 1.1*.

Source: https://www.epa.gov/participatory-science

performance evaluation:

A test that compares sensor data to reference instrument data. Reference instruments are used as they provide highly accurate measurements and are the “gold standard”. See *Section 4.2*.

Source: http://www.aqmd.gov/aq-spec/home

performance metric:

A parameter used to describe the data quality of a measurement device. See *Section 3.4.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

performance targets:

Numeric benchmarks for assessing the measurement performance of an air sensor. See *Section 3.4.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

personal exposure monitoring:

Measurements of an individual's exposure or contact with a health hazard. See *Section 1.1*.

Source: https://www.epa.gov/expobox/exposure-assessment-tools-approaches-direct-measurement-point-contact-measurement

$PM_{1.0}$:

Particles with diameters generally less than 1 micrometer (µm). See *Section 2.1*.

$PM_{2.5}$:

Also called *fine particulate matter*. Fine inhalable particles, with diameters generally less than 2.5 micrometers (µm). See *Section 2.1*.

PM_{10}:

Inhalable particles, with diameters generally less than 10 micrometers (µm). See *Section 2.1*.

polycyclic aromatic hydrocarbons (PAHs):

A group of over 100 different chemicals that are formed during the incomplete burning of coal, oil and gas, garbage, or other organic substances like tobacco or charbroiled meat. PAHs are usually found as a mixture containing two or more of these compounds, such as soot. Some PAHs are manufactured. These pure PAHs usually exist as colorless, white, or pale yellow-green solids. PAHs are found in coal tar, crude oil, creosote, and roofing tar, but a few are used in medicines or to make dyes, plastics, and pesticides. See *Section 2.1*.

Source: https://www.epa.gov/sites/production/files/2015-04/documents/walter_atsdr_pahs.pdf

precision:

Variation around the mean of a set of measurements obtained concurrently by two (2) or more sensors of the same type collocated under the same sampling conditions. The consistency in measurements from identical sensors is often quantified by standard deviation (SD) or the coefficient of variation (CV), with lower values indicating a more precise measurement. See *Section 3.4.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

primary air pollutant:

A pollutant that is emitted into the atmosphere directly from a source such as construction sites, unpaved roads, smokestacks, or fires. See *Section 2.1*.

Source: https://www.epa.gov/pmcourse/what-particle-pollution#where

primary standard:

A type of national ambient air quality standards (NAAQS) that provides public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. See *Section 2.4*.

Source: https://www.epa.gov/criteria-air-pollutants/naaqs-table

-Q-

qualitative measurement:

A measurement that is descriptive, conceptual, and often expressed in words. For example, pollutant concentrations described as "higher" or "lower". See *Section 4.4*.

quality assurance (QA):

Planned steps performed to manage a project and collect, assess, and review data to ensure that measurements meet the data quality needed for the monitoring objective. An example QA activity is developing a plan for air monitoring. See *Section 3.7.2*.

Source: https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

quality assurance project plan (QAPP):

A plan that describes the activities of a monitoring project involved with the acquisition of environmental information whether generated from direct measurements activities, collected from other sources, or compiled from computerized databases and information systems. The QAPP documents the results of a project's technical planning process, providing in one place a clear, concise, and complete plan for the environmental data operation and its quality objectives and identifying key project personnel. The QAPP communicates the specifications for implementation of the project design to all parties and ensures that the quality objectives are achieved for the project. See *Section 3.3*.

Source: https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

quality control (QC):

Steps performed to limit error from instruments or in measurements during a project. Examples of QC activities include collocation, correction of data, maintenance, automatic data checks, and data review. See *Section 3.7.1*.

Source: https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

quantitative measurement:

A measurement which can be expressed using numbers. For example, a pollutant concentration expressed in parts per billion (ppb) or micrograms per cubic meter ($\mu g/m^3$). See *Section 4.4*.

-R-

radiative forcing:

A heating effect caused by greenhouse gases in the atmosphere. Radiative forcing is calculated in watts per square meter, which represents the size of the energy imbalance in the atmosphere. See *Section 2.2*.

Source: https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing

regulatory monitoring:

Monitoring conducted for the purposes of demonstrating compliance with the local, state, or federal air quality regulations. See .

Source: https://www.epa.gov/amtic/regulations-guidance-and-monitoring-plans

remote sensing:

The process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted energy or radiation from a distance (e.g., from satellite-based or aircraft-based instruments). See *Section 2.3*.

Source: https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used?qt-news_science_products=0#qt-news_science_products

representativeness:

A description of how closely a sample reflects the characteristics of the whole. Although challenging to verify, effort should be made to ensure that a sample is representative using techniques such as thorough mixing to obtain homogeneity, duplicate analyses, etc. For example, the data completeness threshold suggested in this report is meant to ensure that measurements averaged to longer time intervals are as representative as possible by covering at least 75% of the time period. See *Section 3.7.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

response time:

The amount of time required for a sensor to respond to a change in concentration. See *Section 3.4.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

-S-

scatter plot:

A plot that shows the relationship between two variables, one on the x-axis and one on the y-axis. For sensor data, scatter plots can help explore the relationship between two parameters of interest, understand how a sensor compares to a regulatory monitor, or understand if a sensor overestimates or underestimates pollutant concentrations. See *Section 3.6.2*.

Source: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=354208

secondary air pollutant:

A pollutant that is formed when other primary air pollutants react in the atmosphere. An example of a secondary pollutant is ground-level ozone (O_3), which forms from chemical reactions involving airborne nitrogen oxides (NO_x), airborne volatile organic compounds (VOCs), and sunlight. See *Section 2.1*.

Source: https://www.mrgscience.com/ess-topic-63-photochemical-smog.html

secondary standard:

A type of national ambient air quality standards (NAAQS) that provides public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings. See *Section 2.4*.

Source: https://www.epa.gov/criteria-air-pollutants/naaqs-table

sensor lifespan:

The time period during which the air sensor is designed to function normally. See *Appendix C*.

sensor network:

Two (2) or more air sensors that collect pollutant concentration or other data (e.g., relative humidity, temperature) from different locations and transmit the measurements to a central repository. See *Section 3.3*.

sensor node:

An individual sensor within a sensor network. See *Section 1.1*.

short-term:

A time period covering seconds to weeks. See *Section 2.2*.

specification sheet:

A document that presents the detailed technical aspects and characteristics of an item or product. See *Section 3.4.1*.

specificity:

The ability of a sensor to measure the pollutant of interest (*target pollutant*). See *Section 4.4*.

standard operating procedure (SOP):

A set of written instructions that detail the one-time and repetitive activities to be conducted or followed within an organization. An SOP provides individuals with the information to perform a job properly, which facilitates consistent conformance to technical and quality system requirements and supports data quality. See *Appendix B*.

Source: https://www.epa.gov/sites/production/files/2015-06/documents/g6-final.pdf

standards:

As related to sensors, a voluntary process where technology testing methods are agreed upon by authorities, manufacturers, customers, and others invested in the performance of the technology. See *Section 4.3.1*.

State Implementation Plan (SIP):

A collection of regulations and documents used by a state, territory, or local air district to implement, maintain, and enforce the National Ambient Air Quality Standards (NAAQS), and to fulfill other requirements of the Clean Air Act. See *Section 2.4*.

Source: https://www.epa.gov/air-quality-implementation-plans/basic-information-about-air-quality-sips

supplemental monitoring:

An application where sensors are placed in locations that do not have an existing regulatory monitor(s). Typically, the goal is to fill in gaps in areas where there are no or limited regulatory monitors or to identify sources of interest or locations requiring further study and/or monitoring. See *Section 1.1*.

Source: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=354208

-T-

target pollutant:

A pollutant of interest for a measurement. See *Section 3.4.1*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

time averaging interval:

The time period over which raw measurements are averaged. See *Appendix E*.

-U-

ultrafine particles (UFP):

Particles in the atmosphere that have diameters generally less than 0.1 micrometer (µm). UFP are created by combustion processes and chemical reactions in the atmosphere. See *Section 2.1*.

Source: https://www.epa.gov/pmcourse/particle-pollution-exposure

underestimate:

Also referred to as *under-report*. Sensor measurements are lower than the reference monitor measurements. See *Section 3.6.2*.

Source: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

upwind:

Where air moves through before it goes over an area of interest. See *Section 2.1*.

Source: https://www.epa.gov/interstate-air-pollution-transport/what-interstate-air-pollution-transport

-V-

violation:

Occurs when a measured concentration of a criteria pollutant exceeds the concentration level for the averaging period specified by the National Ambient Air Quality Standards (NAAQS) for specific criteria over a specified timeframe. See *Section 2.4*.

visibility:

The degree of perceived clarity (e.g., contrast, coloration, and texture elements) when viewing objects at a distance. Visibility can be impaired by haze caused by air pollutant emissions from numerous sources distributed over a wide geographic area. See *Section 2.1*.

Source: https://www.epa.gov/sites/production/files/2015-05/documents/1999hazefacts.pdf

volatile organic compounds (VOCs):

VOCs include a variety of chemicals that have a high vapor pressure and low water solubility. Many VOCs are human-made chemicals that are used and produced in the manufacture of paints, pharmaceuticals, and refrigerants. VOCs typically are industrial solvents, such as trichloroethylene; fuel oxygenates, such as methyl tert-butyl ether (MTBE); or by-products produced by chlorination in water treatment, such as chloroform. VOCs are often components of petroleum fuels, hydraulic fluids, paint thinners, and dry-cleaning agents. See *Section 2.1*.

Source: https://www.epa.gov/indoor-air-quality-iaq/what-are-volatile-organic-compounds-vocs

verification:

The process of evaluating the completeness, correctness, and conformance/compliance of a specific data set against the method, procedural, or contractual requirements. See *Section 3.3*.

Source: https://www.epa.gov/sites/default/files/2015-06/documents/g5-final.pdf

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