EPA Tools and Resources Webinar

FRMs/FEMs and Sensors: Complementary Approaches for Determining Ambient Air Quality

Andrea Clements and Robert Vanderpool
Center for Environmental Measurement and Modeling
US EPA Office of Research and Development

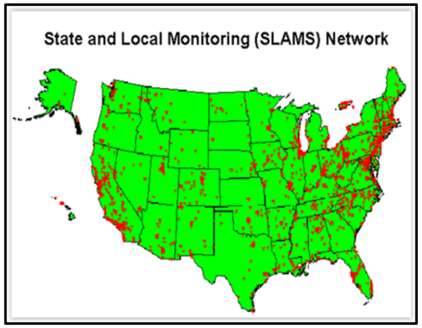
December 18, 2019

Presentation Outline

- Purpose and regulatory requirements for ambient air monitoring
- Federal Reference Methods (FRMs)
- Federal Equivalent Methods (FEMs)
- Performance specifications for regulatory monitoring of criteria pollutants
- Domestic and international impacts of accurate air monitoring methods
- Identification of need for Air Sensors
- Key differences between FRMs/FEMs and Air Sensors
- Definition of Air Sensors
- Design of commercially available Air Sensors
- Performance characteristics of Air Sensors
- Selection criteria of regulatory versus sensor-based air monitors

Background

- Adverse health effects of air pollution exposure have long been recognized.
- World Health Organization (WHO) estimates that approximately 4 million annual deaths occur worldwide due to exposure to ambient air pollution.
- The U.S. Clean Air Act (CAA) requires nationwide monitoring of six “criteria pollutants” (CO, O_3, SO_2, NO_2, Pb and particulate matter) known to pose public health threats.
- EPA’s nationwide pollutant monitoring network represents an important tool for:
    - Assessing the public’s exposure to criteria pollutants.
    - Evaluating the effectiveness of pollutant control strategies



Regulatory Monitors

- CAA specifies the following:
    - Setup and ongoing operation of nationwide air monitoring stations
    - Compliance monitors must be formally designated as either Federal Reference Methods (FRMs) or Federal Equivalent Methods (FEMs)
- Both FRMs and FEMs have very strict measurement performance criteria to ensure that data supports accurate and effective air quality management decisions.
- EPA ORD (RTP, NC) is Congressionally mandated to review new instrument designs and formally designate approved monitors as either FRMs or FEMs.
    - Formal announcement of new instrument designations takes place through *Federal Register* notices

FRM and FEM Samplers and Analyzers

FRMs

- Designed to provide the most fundamentally sound and scientifically defensible concentration measurement
- FRM measurement principles for each criteria pollutant are published in 40 Code of Federal Regulations (CFR) Part 50
- FRMs serve as the basis of comparison upon which to judge other measurement methods

FEMs

- Intended to provide a comparable level of compliance decision making quality as provided by FRMs
- May include newer, innovative technologies to reduce overall operating cost and to achieve multiple monitoring objectives (e.g, real-time reporting for health studies and for issuing timely public health advisories)

FRM/FEM Methods Designation Program

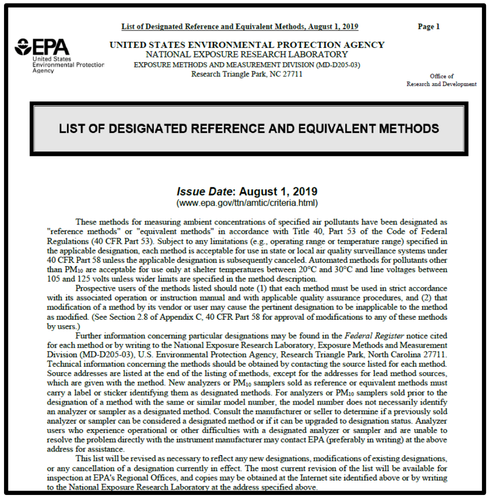
FRM & FEM Methods Designation Program

- Actively conducts technical and administrative reviews of new candidate FRMs and FEMs for their approval
- Provides reviews of **modification requests** to proposed changes in a designated FRM or FEM analyzer's hardware, software, firmware and/or operating procedures
  - Modification request reviews are required to ensure that the analyzer's accurate measurement response is maintained
- Reviews include administrative review of a manufacturer's submitted performance data
  - In some cases, laboratory and/or local field evaluation of candidate instruments is required in order to make confident designation decisions
- During the last 5 years, **116 FRM/FEM** designations decisions were formally made

FRM/FEM Methods Designation Program

- **Designated Reference and Equivalent Methods**
  - List of FRMs and FEMS can be found here:

    https://www.epa.gov/amtic/air-monitoring-methods-criteria-pollutants
  - Updated twice a year



List of Designated Reference and Equivalent Methods, August 1, 2019 — Page 1

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
NATIONAL EXPOSURE RESEARCH LABORATORY
EXPOSURE METHODS AND MEASUREMENT DIVISION (MD-D205-03)
Research Triangle Park, NC 27711

Office of Research and Development

LIST OF DESIGNATED REFERENCE AND EQUIVALENT METHODS

***Issue Date*: August 1, 2019**
(www.epa.gov/ttn/amtic/criteria.html)

These methods for measuring ambient concentrations of specified air pollutants have been designated as "reference methods" or "equivalent methods" in accordance with Title 40, Part 53 of the Code of Federal Regulations (40 CFR Part 53). Subject to any limitations (e.g., operating range or temperature range) specified in the applicable designation, each method is acceptable for use in state or local air quality surveillance systems under 40 CFR Part 58 unless the applicable designation is subsequently canceled. Automated methods for pollutants other than PM_{10} are acceptable for use only at shelter temperatures between 20°C and 30°C and line voltages between 105 and 125 volts unless wider limits are specified in the method description.

Prospective users of the methods listed should note (1) that each method must be used in strict accordance with its associated operation or instruction manual and with applicable quality assurance procedures, and (2) that modification of a method by its vendor or user may cause the pertinent designation to be inapplicable to the method as modified. (See Section 2.8 of Appendix C, 40 CFR Part 58 for approval of modifications to any of these methods by users.)

Further information concerning particular designations may be found in the *Federal Register* notice cited for each method or by writing to the National Exposure Research Laboratory, Exposure Methods and Measurement Division (MD-D205-03), U.S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711. Technical information concerning the methods should be obtained by contacting the source listed for each method. Source addresses are listed at the end of the listing of methods, except for the addresses for lead method sources, which are given with the method. New analyzers or PM_{10} samplers sold as reference or equivalent methods must carry a label or sticker identifying them as designated methods. For analyzers or PM_{10} samplers sold prior to the designation of a method with the same or similar model number, the model number does not necessarily identify an analyzer or sampler as a designated method. Consult the manufacturer or seller to determine if a previously sold analyzer or sampler can be considered a designated method or if it can be upgraded to designation status. Analyzer users who experience operational or other difficulties with a designated analyzer or sampler and are unable to resolve the problem directly with the instrument manufacturer may contact EPA (preferably in writing) at the above address for assistance.

This list will be revised as necessary to reflect any new designations, modifications of existing designations, or any cancellation of a designation currently in effect. The most current revision of the list will be available for inspection at EPA's Regional Offices, and copies may be obtained at the Internet site identified above or by writing to the National Exposure Research Laboratory at the address specified above.

- **Programmatic challenge**
  - Application review activity is at a historic high level
  - EPA ORD has no control over the number, type or complexity of the applications received at any given time
  - Effective management is required to ensure that reviews are conducted within Congressionally mandated deadlines

FRM/FEM Critical Operating Specifications

- Accuracy
- Precision
- Range
- Detection Limit
- Pollutant Specificity
- Freedom from Co-Pollutant Interferences
- Noise
- Drift (short-term and long-term)
- Lag/Rise/Fall (gas analyzers)
- Multi-Site Measurement Performance

The quality of health-based management decisions is *directly proportional to the quality of the pollutant's measurement data.*

Each specification has strict testing requirements and acceptance criteria.
A candidate instrument must pass <u>ALL</u> of these tests in order to be approved by EPA.

Manufacturers can successfully design FRM and FEM instruments from the "ground-up" because EPA's testing requirements, testing procedures, and acceptance criteria are explicitly specified in the regulations.

Overall QA/QC Initiatives

- Instrument manufacturing quality assurance/quality control (QA/QC) (e.g., ISO 9001) to ensure instruments are manufactured according to approved specifications
- Proper siting of FRMs/FEMs to meet regulatory requirements
- Competent instrument setup, calibration, operation, maintenance, and troubleshooting
- Periodic internal and external instrument audits- Performance Evaluation Program (PEP)
- Periodic internal and external audits of analytical laboratories
- Inspection and validation of data prior to final data reporting and usage

In addition to the formal instrument FRM and FEM designation process, there are multiple initiatives to ensure that accurate network data are produced for its intended use.

Impact of Accurate Air Quality Data

- Determine compliance with air quality regulations
- Determine nationwide trends and distribution of air pollution
- Evaluate effectiveness of pollutant control strategies
- Provide data for development/evaluation of numerical air quality models
- Provide exposure data for public health studies
- Enable timely public health advisories
- Provide input to National Ambient Air Quality Standards (NAAQS) reviews and revisions
- Evaluation of alternative technologies (e.g., sensors)
- Inputs for permit applications
- Development of State Implementation Plans (SIPs)

The scope and magnitude of these benefits are directly influenced by the quality of our nationwide pollutant measurements.

There are real and dramatic costs (both financial and health-based) associated with making incorrect decisions based on monitoring data that is of inherently poor quality.

Domestic and International Impact

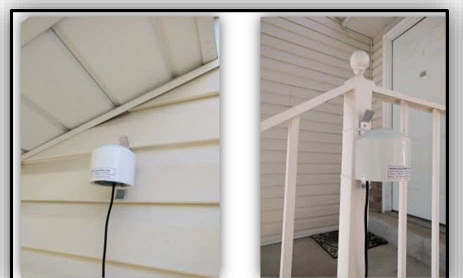
- EPA ORD's approved FRM/FEM monitoring methods are domestically and internationally recognized as the gold standard of air monitors by Government regulatory programs, instrument manufacturers, air quality researchers, health scientists and the public.
- About 80% of designated FRM/FEM instrument sales are now overseas.
- EPA's designation "stamp of approval" on manufactured air quality instruments is a huge marketing advantage for the instrument manufacturer.
- With worldwide deployment and operation of EPA's FRM/FEM samplers and analyzers, users are ensured that accurate data quality is being obtained to make scientifically defensible public health assessments and effective air quality management decisions.

United States Environmental Protection Agency

Role of Sensors

- Goal of the nationwide regulatory monitoring network is to assess the public’s exposure to the criteria pollutants and for evaluating the effectiveness of pollutant control strategies
- Many other places and ways in which people want to make air quality measurements
  - **Innovation** is needed in technology to make these measurements possible

Regulatory Monitoring Site



More local measurements and temporary sites

Educational exploration

Mobile measurements carried by individuals

Mobile measurements using vehicles

Key Differences

	Reference Monitors	Low-Cost Sensors
Typical Purchase Cost	$15,000 to $40,000 (USD)	$200 to $5,000 (USD)
Staff Training	Highly trained technical staff	Little or no training to operate. May need more training to interpret data
Operating Expense	Expensive – shelter, technical staff, maintenance, repair, quality assurance.	May be less expensive – replacement, data streaming, data management.
Siting Location	Fixed Location. (climate controlled building/trailer needed)	More portable. May require weather shielding. Siting can be easier due to lower flow rates but more tricky because of data streaming.
Data Quality	Known and consistent quality in a variety of conditions.	Unknown. Can vary from sensor to sensor, in different weather conditions, and in different pollution environments.
Operating Lifetime	10+ Years (calibrated and operated to maintain accuracy).	Short (1 year) or Unknown (may become less sensitive over time).
Regulatory Monitoring?	Yes	No

Definition of Air Sensor

OEM (Original Equipment Manufacturer) sensors

- "Raw" optical, metal oxide, or electrochemical sensor
- Little to no data processing or interface on the sensor
- Relatively few different OEM types for a given pollutant

Sensor/Sensor System/Sensor Device/Sensor Node (many names)

- One or more OEM sensors integrated into a device with data/power management into some kind of housing
- May be passive or active sampling
- Data generally reported in real-time at high time resolution
- Integrators design for different user needs/applications

Integration of an OEM sensor impacts performance – must test the system/device/node

OEM Sensors – Particulate Matter (PM)

- **PM sensors currently use optical OEM sensors**
  - Particles scatter light from a laser or LED as they move through the measurement cell
  - Scattered light is measured by a detector and the signal is used to estimate either the volume of an ensemble of particles and/or the number of particles in the air
  - Count estimate is then converted to mass concentration based on mass calibration or a density estimate

- **Humidity influences**
  - Increased humidity causes particles to grow, which increases the volume of the particle (but not the actual mass of the PM)
  - Can cause the mass to be over-estimated

United States Environmental Protection Agency

OEM Sensors - Gases

- **Electrochemical sensors**
  - Temperature and humidity sensitivity
  - Low-power
  - Cross-sensitivities

- **Metal oxide sensors**
  - Higher power draw due to needing to heat the sensor to 200-500° C to increase sensitivity and response time
  - Slow startup due to warming up the sensor
  - Low humidity sensitivity
  - Cross-sensitivities

United States Environmental Protection Agency

Commercially Available Air Sensors

Sensor Data Management

Sensors

Data transmits…

Bluetooth transmission to user's phone with app

or

Embedded cell modem (or user adds)

or

No transmission and data stored to memory card

Received by…

Manufacturer's server/cloud

and/or

User's server

And then…

Raw data immediately shown to public

or

Raw data are private access

or

Algorithms adjust data, then share or private access

Key Considerations:

- ***Where is the data stored?***
- ***What volume of data must be managed?***
- ***How can the data be accessed?***
- ***Who owns the data?***

A lot of variety in data flow and accessibility!

Sensor Data Adjustments

Data adjustments and algorithms take many forms

- Factory “calibration” → Manufacturer “calibration” → Field collocation → Network correction check
- Manufacturer applied data correction → user applied data correction
- Simple linear regression → more complicated data model → machine learning/artificial intelligence (AI)

There is room for debate on what strategies make sense based on application

Table 1. Sensor Data Adjustment Parameters: Defendable and Questionable

defendable parameters	questionable parameters
• relative humidity, for which measurement artifact has been established	• wind speed or direction
• temperature, for which measurement artifact has been established	• gases for which no cross-sensitivity is indicated
• other gases for which cross-sensitivity has been established	• data from neighboring monitors (reference-grade or sensor) that are not proven as suitable reference point[a]
• elapsed time since manufactured or deployed, if aging has been demonstrated to cause change in sensor response.	• local emission information or surrogates for emissions (e.g., traffic patterns, population density)
• accessory measurements indicating aerosol refractive index, for pm sensors	• temporal factors other than elapsed time of use (e.g., time of day, day of week)
• autozero data, if equipped to self-zero	• atmospheric mixing height
• monitors in close proximity, if established to have comparable data under specific conditions[a]	• location relative to sources (e.g., proximity to a road)

[a]This is a subject of needed research and likely location-specific, as well as pollutant-specific.

Hagler et al., 2018, “Air Quality Sensors and Data Adjustment Algorithms: When Is It No Longer a Measurement?”, ES&T

Performance Characteristics

Sensors have varying performance – assessment prior to use is critical and most valuable if evaluated under similar conditions of planned use.

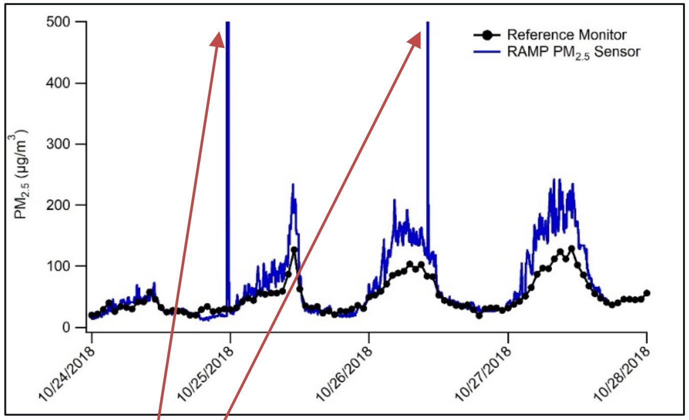
Collocation is the process by which a reference monitor (FRM/FEM) and non-reference monitor (sensor) are operated at the same time and place under real world conditions for a defined evaluation period.

- Sensor performance can be evaluated by comparing the data to that of the FRM/FEM
- Sensor data accuracy can be improved by developing a data adjustment equation
- Collocation periods before and after deployment provide the chance to evaluate sensor drift
  - For long deployments, mid-study collocation is helpful

Performance Characteristics

Environmental related artifacts are common and performance can change over time.

- ***Relative humidity*** – High humidity may cause PM sensors to overestimate the mass concentration. Gas sensors often show sensitivity.
- ***Temperature*** – Sensors may show sensitivity.
- ***Co-Pollutants*** – Sensors may react to other pollutants which can "interfere" with how the sensor responds to the target pollutant.
- ***Time*** – Drift may be apparent over time. Sensors may become less responsive as they age.
- ***Noisy Data*** – Spurious data points may or may not be evident. May be related to data logging errors, electronic noise, etc.



Real transient event? Logging error? Sensor issue?

EPA United States Environmental Protection Agency

Performance Characteristics

The majority of sensors report little to no diagnostic information nor provide means by which to check operational parameters.

FRM/FEM grade instruments

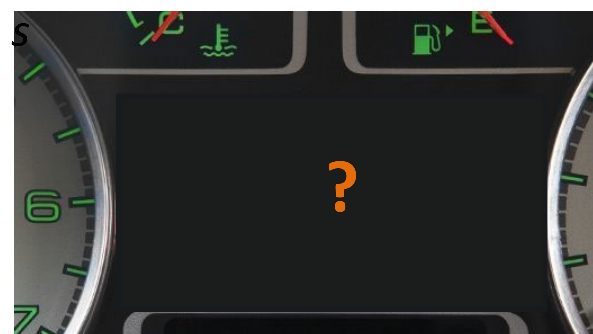
- Provide diagnostic information such as status indicators, flow rates, internal lamp voltages, etc., which may serve as warning signs of performance deterioration
- Operators can independently validate some parameters and conduct maintenance work to keep the instrument running optimally

Sensors

- Rarely have information beyond a timestamp and concentration value
- Usually not designed for validation checks or maintenance

FRM/FEM instruments

Sensors

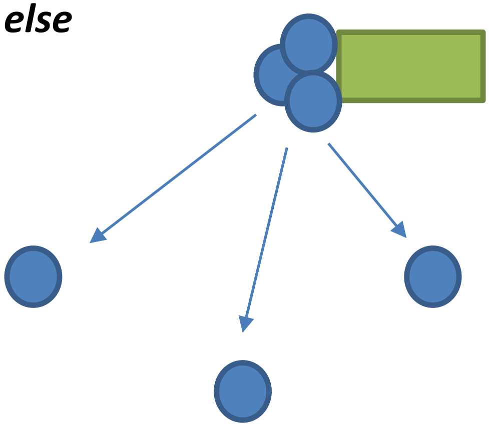


Improving Sensor Performance

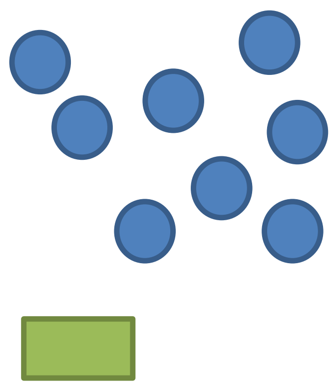
A variety of strategies to overcome sensor performance issues are in development.

1. Data Cleaning
2. Longer time averaging
3. Data adjustment algorithms
4. Network calibration techniques

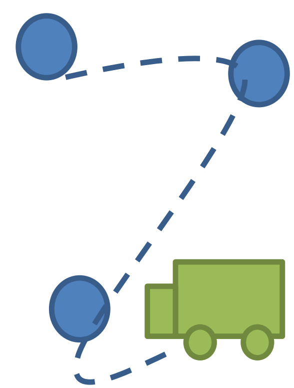
Training approach: Collocate with reference for awhile, then redeploy somewhere else



Network approach: Compare/correct between neighboring sites



Network with mobile reference: Drive-by calibration of network



Method Selection

FRMs/FEMs and sensors provide complementary approaches for measuring ambient air quality.

When selecting a method, start by asking some key questions:

1. Why are you making measurements?
2. What do you want to measure?
3. How will the data be used?
4. What measurement frequency is needed?
5. How long will you need to make measurements?
6. How will you check the data quality?

EPA United States Environmental Protection Agency

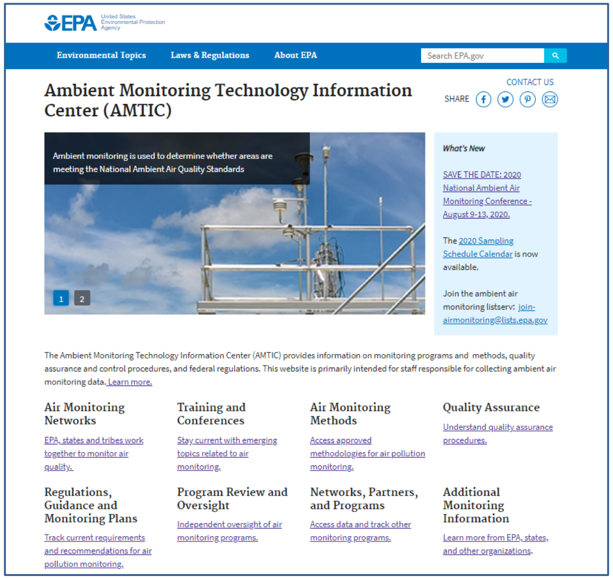
Method Selection

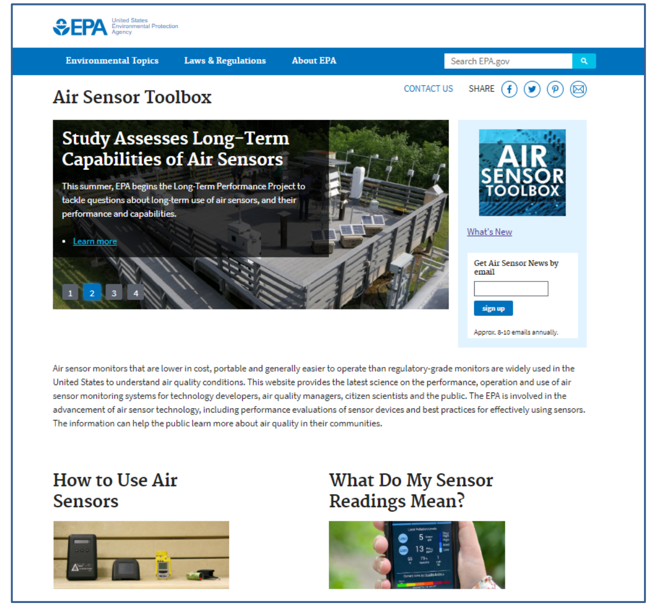
FRMs/FEMs and sensors provide complementary approaches for measuring ambient air quality.

- Measurements for regulatory use
- Data used for compliance decisions
- Need high confidence in the data
- Want established data quality control and assurance methods

- Measurements for non-regulatory use
- Data used for informational purposes
- Demonstrated accuracy or precision is “good enough” for intended application
- Want data at high time resolution
- Need smaller or more portable devices
- Limited by cost, power, communication needs and/or data handling constraints

Resources





Learn more about FRM/FEM instruments and quality assurance and control procedures in the **Ambient Monitoring Technology Information Center (AMTIC)**: www.epa.gov/amtic

Find guides, resources, performance evaluations and information about ongoing research involving air sensors in the **Air Sensor Toolbox**: www.epa.gov/air-sensor-toolbox

Contacts

Robert (Bob) Vanderpool (FRM/FEM program)
Aerosol Research Engineer
US EPA Office of Research and Development
vanderpool.robert@epa.gov
919-541-7877

Andrea Clements (Air Sensors)
Physical Scientist
US EPA Office of Research and Development
clements.andrea@epa.gov
919-541-1363