Air Quality Sensors: Technology and Advances

17th Annual Air Quality and Health Workshop

British Columbia Lung Association

Tuesday, February 11th, 2020

Andrea L. Clements, Ph.D.
U.S. EPA Office of Research and Development
clements.andrea@epa.gov

Motivation

- Air sensors are becoming more popular and widely used.

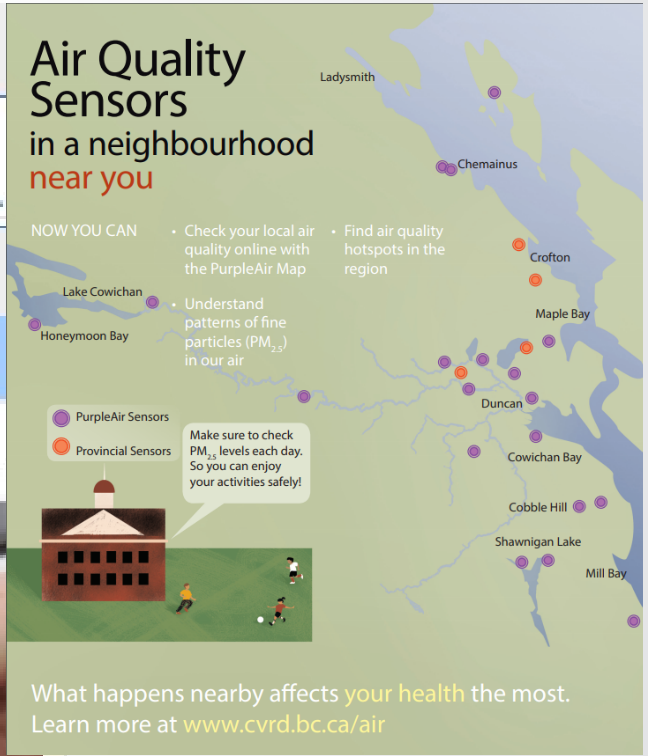
***Helps make air quality data more accessible**

The American Citizen's Guide to Clean Air

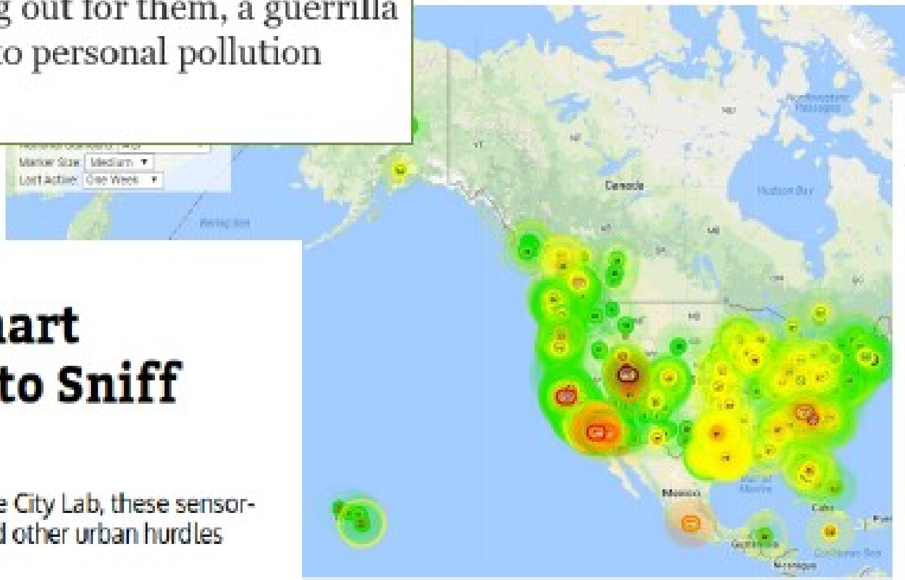
Unsure if the government is looking out for them, a guerrilla network of "breathers" has turned to personal pollution monitors.

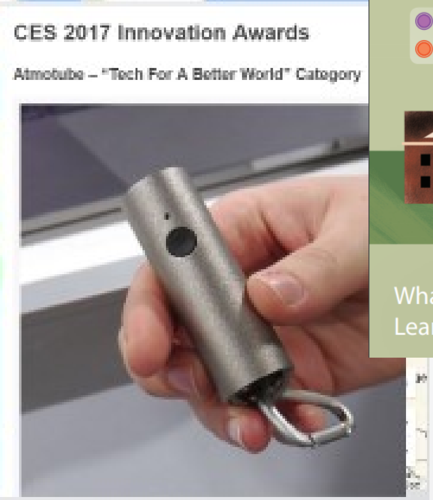
Denver Schools Will Help Monitor Air Quality

***Marketed directly to consumers**



***Data displayed on maps**





CITYFIXER

Cambridge's Fleet of Smart Garbage Trucks Is Here to Sniff Out Problems

A collaboration between the city and MIT's Senseable City Lab, these sensor-equipped vehicles can detect gas leaks, potholes, and other urban hurdles across their paths.

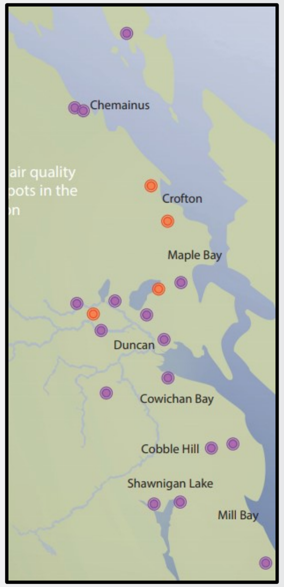
Motivation

- Air sensors are being used for a wide variety of applications.

Short-term use for emergencies: Use of sensors during wildfires.

Exploratory applications to detect local source impacts: Residential wood smoke, local transportation sources, and industrial sources.

Finer-scale air quality information: Increasing the number of air quality monitoring locations.



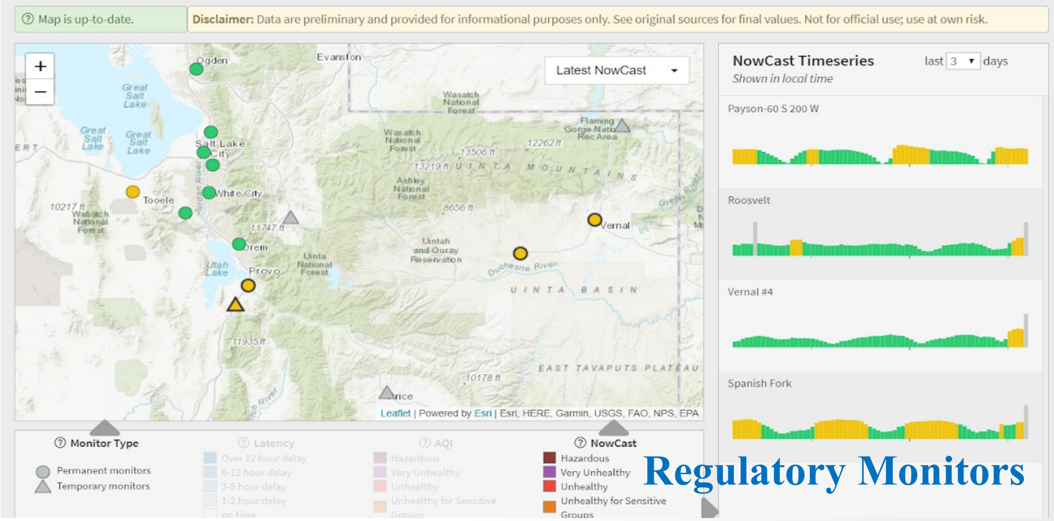
Environmental awareness and education: Sensors placed at community centers, parks, and schools.

Motivation

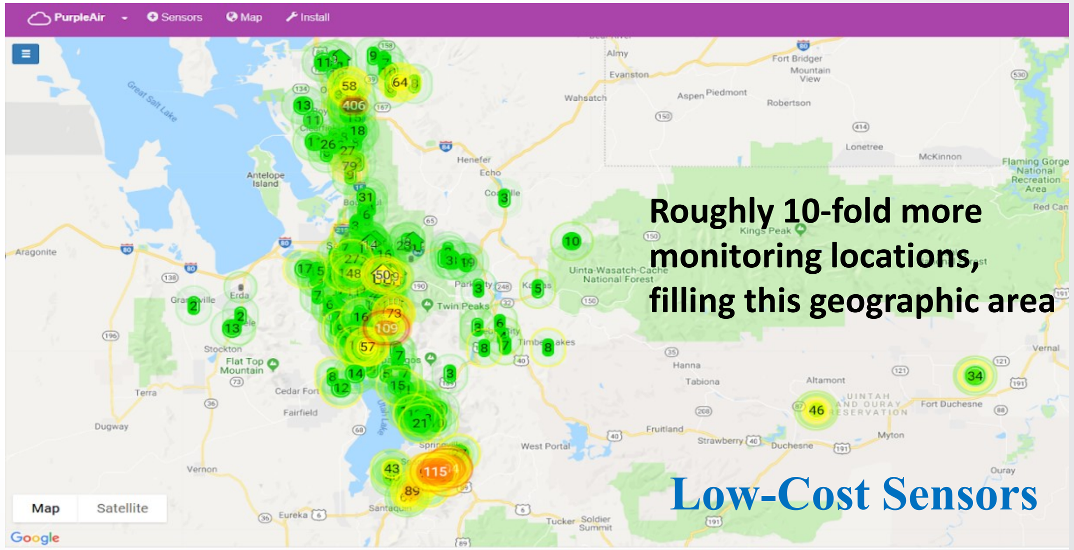
- Rapid expansion in the use of sensors creates a growing need to understand the data being produced.
  - Sensors can outnumber regulatory monitors.
  - Significant confusion if the data disagree.

- Great excitement for more localized air quality data.
  - Especially valuable for certain situations (e.g., wildfire smoke)

CAVEAT: It is important to understand the key differences between sensor and regulatory technologies <u>and</u> how sensor data are handled.



Regulatory Monitors



Roughly 10-fold more monitoring locations, filling this geographic area

Low-Cost Sensors

Presentation Outline

- Definition of air sensors
- Types of air sensors on the market today
- Current state of the technology for various pollutants
- Sensor data management
- Sensor data adjustments
- Understanding Sensor Performance
- Available resources
- Questions

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
- Developers design systems for different user needs/applications

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

Commercially Available Air Sensors

State of Sensor Technology – PM

Particulate Matter (PM)

- Several Options ($200s to $1000s)
- $PM_{2.5}$: Good correlation but often over- or under-estimate concentrations
- PM_{10}: Generally not measured well
- Influenced by particle type, temperature, and relative humidity

Black Carbon

- In development
- Price points currently ~$15K

Other Particle Species/ Sizes

- No speciation sensors currently available
- Optical particle sizers in development ~$12K
- Ultrafine particle sensors in development

State of Sensor Technology – PM

- **Benefits**
  - PM sensors are widely distributed.
  - Most PM sensors show good agreement between sensors of the same type.
  - Many exhibit reasonable correlation with reference, although can show bias.
  - Most sensors experience minimal downtime and good data recovery.
  - PM sensors have a reasonable life span.
- **Considerations**
  - Temperature and humidity effects, especially high humidity.
  - Under-reporting or over-reporting of concentrations.
  - Does not detect very small particles (< 0.3 µm).
  - Does not reliably measure large particles (> ~5 µm).

State of Sensor Technology - Gases

Carbon Monoxide (CO)

- Few options ($500s to $1000s)
- Finite lifetimes
- Good accuracy and fairly reliable with collocation

Ozone (O_3)

- Fairly accurate and reliable with collocation
- Must consider concentration range

Nitrogen Dioxide (NO_2)

- Few options ($500s to $1000s)
- Highly variable performance
- Strong cross-sensitivities

Sulfur Dioxide (SO_2)

- Difficulty measuring low-concentrations
- Highly variable performance
- Strong cross-sensitivities especially to meteorology

State of Sensor Technology – 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

State of Sensor Technology – Gases

- **Benefits**
  - Gas sensors are widely available.
  - Performance is getting better. An increasing number of O_3, NO_2, and CO sensors are on the market with adequate test results.
- **Considerations**
  - Gas sensors have strong cross-sensitivities. The use of multiple sensors (e.g., $NO_2 + O_3$) and data adjustment algorithms show promise in improving correlations with reference methods.
  - Gas sensors can lose sensitivity after about 6 months to 2 years.
  - SO_2 sensors are not yet effective at the low concentrations seen in ambient air.

Gaseous Sensors

Sensor Image	Make (Model)	Est. Cost(USD)	Type	Meas.	*Field R^2	*Lab R^2	Summary Report
	2B Technologies (POM)	$4,500	UV absorption (FEM Method)	O_3	1.00	0.99	PDF (1,295 KB)
	Aeroqual (AQY) Ver. 0.5	$3,000	Electrochem	NO_2	0.77	0.98	PDF (1,158 KB)
			Metal Oxide	O_3	0.95	0.98	PDF (1,163 KB)
	Aeroqual (S-500)	$500	Metal Oxide	O_3	0.85	0.99	PDF (1,197 KB)
	Air Quality Egg Ver. 1	$200	Metal Oxide	CO	0.0		
				NO_2	0.40		
				O_3	0.85		
	Air Quality Egg Ver. 2	$240	Electrochem	CO	0.0		
				NO_2	0.0		
	Air Quality Egg Ver. 2	$240	Electrochem	O_3	0.0 to 0.20		
				SO_2	n/a		

Evaluation summary excerpt from AQ-SPEC

http://www.aqmd.gov/aq-spec/evaluations/summary-gas

State of Sensor Technology

VOCs/ HAPs

- Most measure Total VOCs (tVOCs) rather than speciated VOCs
- Commonly used for sentinel leak detection
- Strong interest and development work happening
- Miniaturization of analytical grade instruments

Key:
VOCs = volatile organic compounds
HAPs = hazardous air pollutants

Ammonia

- In development
- Price points likely > $5K and up

Nitric Acid

- No sensors currently available

Formaldehyde

- In development
- Price points currently ~$15K

State of sensor technology – VOCs

- **Benefits**
  - Research, development, and evaluation is continuing on both high-end and lower cost instrumentation.
  - PID (photoionization detector) sensors, which provide a qualitative total VOC measurement, can be useful for leak detection and/or sample triggering.
- **Considerations**
  - Sensors which measure individual VOC concentrations, such as benzene, are not yet widely available.
  - Detection limits for many tVOC sensors tend to be too high for ambient/outdoor applications but may find applications within facilities or at facility fence lines.
  - Available technologies tend to have higher price points.

A VOC sensor can be used to trigger a canister sample for more detailed offline analysis

Sensor Data Management

Data transmits…

Data stored locally to memory card (access by card, cord or local network)

or

Bluetooth transmission to user's phone (view or transmit)

or

User supplied wifi (view or transmit)

or

Embedded or user supplied modem (cellular or satellite)

Received by…

Local Device (phone, tablet or computer)

or

Manufacturer's server/cloud

and/or

User's server

Data Display…

Data immediately shown to public

or

Data are private access

Question:
Is raw data or adjusted data displayed?

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

- **Sensor data adjustments and algorithms take many forms**

Derived for OEM sensors in the factory

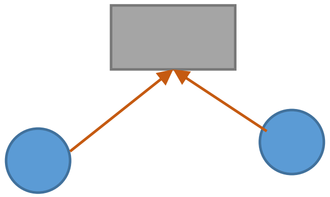
Derived by a manufacturer after the OEM has been integrated into a sensor device

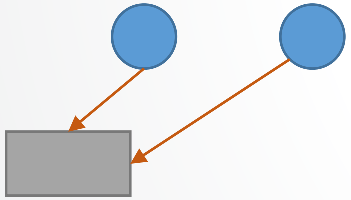
Derived by a user in the field by collocation with a reference monitor

Sensor Data Adjustments – Example 1

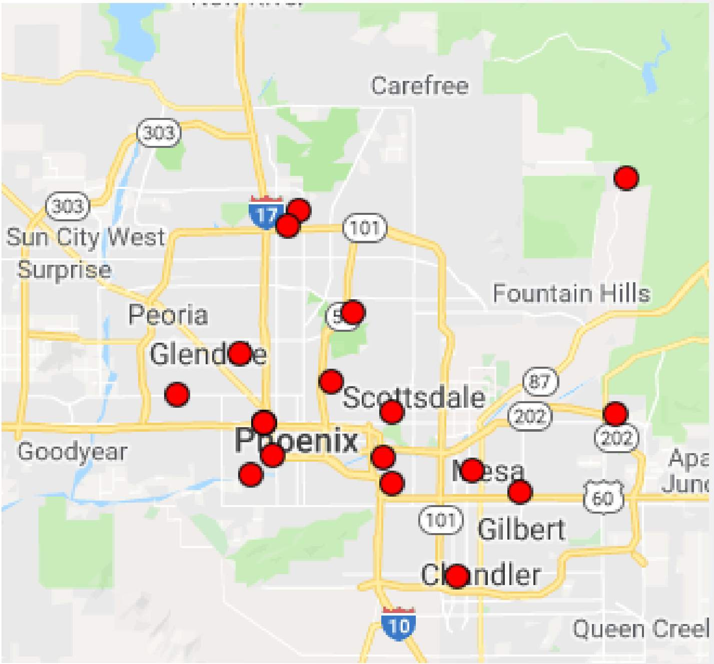
- **Data adjustment may be supplemented by a network correction check**

Comparison (potential correction) based on nearest regulatory monitor.





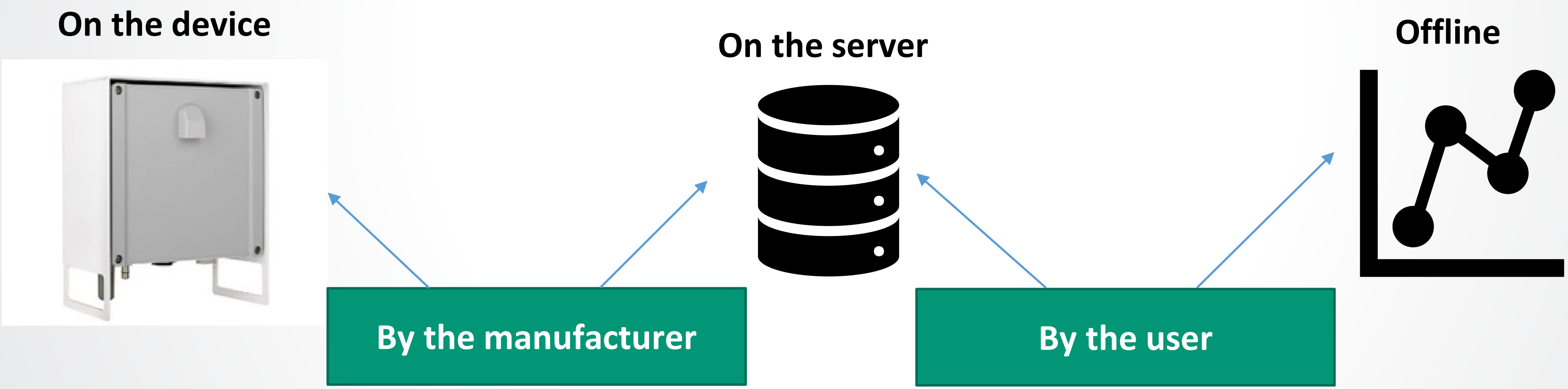
Could include comparison (and correction) based on nearest sensor too.



Must be careful not to over-correct and remove real variations in pollutant concentration.

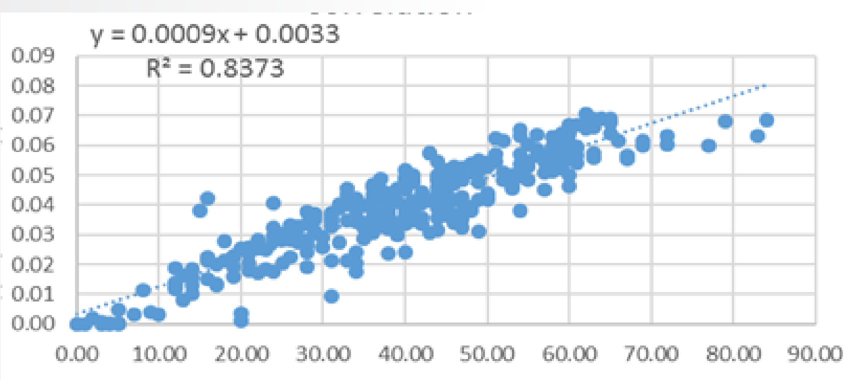
Sensor Data Adjustments – Example 2

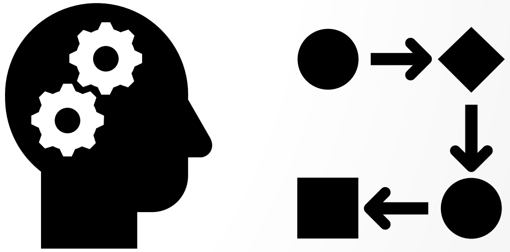
- **Data corrections can be applied by…**
  - The manufacturer, on the device or after the data gets to the server
  - A user, through the user interface or offline



Sensor Data Adjustments – Example 3

- **Data corrections can be….**
  - Simple (e.g., linear regression)
  - Complicated (e.g., multivariate model)
  - Involve machine learning or artificial intelligence





More complicated models tend to be needed for gas sensors due to cross-sensitivities (response to multiple pollutants)

Sensor Data Adjustments – Summary

- **Sensor data adjustments and algorithms take many forms**
  - Data adjustment equations can be derived for OEM sensors in the factory, by a manufacturer after the OEM has been integrated into a sensor device, or by a user in the field by collocation with a reference monitor
  - May be supplemented by a network correction check
  - Data corrections can be applied by the manufacturer on the device or after the data gets to the server or it can be applied by a user through the user interface or offline
  - Data corrections can be simple (e.g., linear regression), complicated (e.g., multivariate model), or even involve machine learning or artificial intelligence

<u>It is important to know:</u>

✓ Why data is being adjusted?
✓ Where and how data is adjusted?
✓ How were the adjustments derived?
✓ What data is being used in the adjustment?

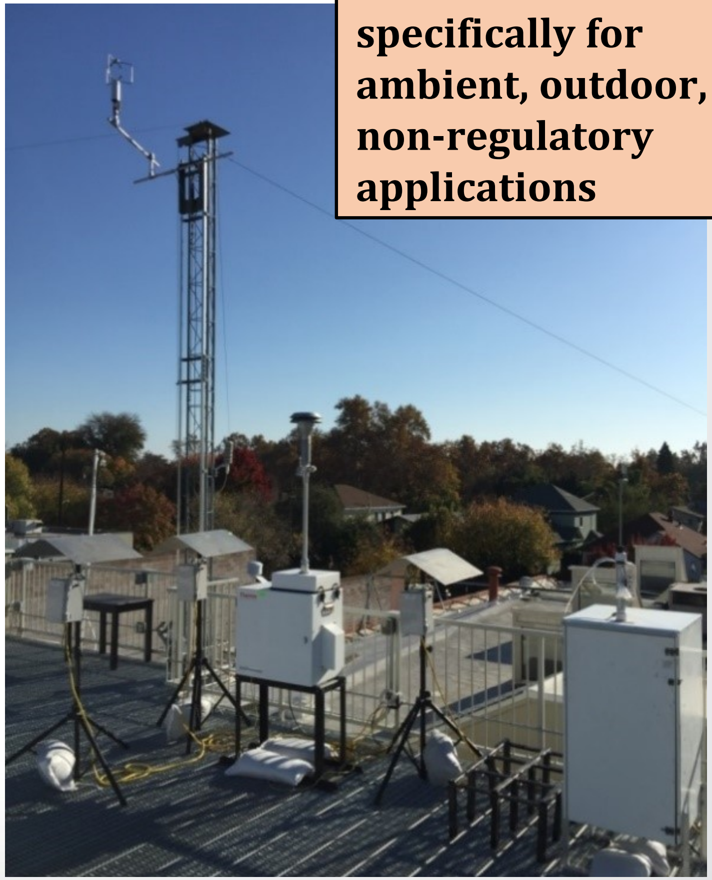
Understanding Sensor Performance

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

U.S. EPA conducts performance evaluations specifically for ambient, outdoor, non-regulatory applications

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.

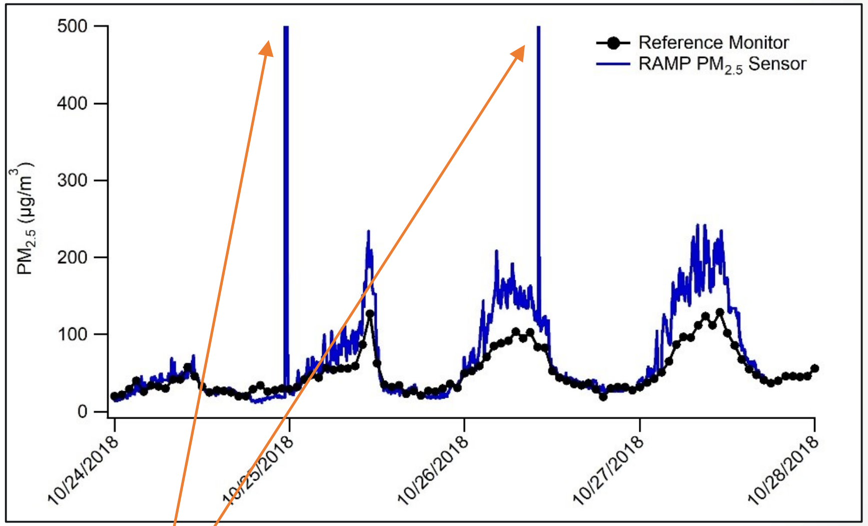


FRM/FEM = Federal Reference Method/Federal Equivalent Method

Understanding Sensor Performance

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.



Holder et al.

Real transient event? Logging error? Sensor issue?

Understanding Sensor Performance

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

FRM/FEM grade instruments

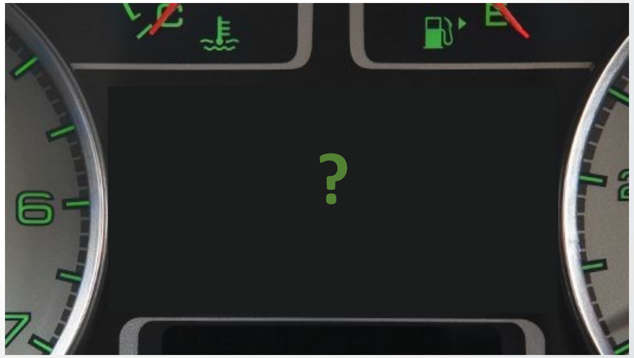
- Provide diagnostic information such as status indicators, flow rates, internal lamp voltages, etc., which may serve as warning signs of performance deterioration.
- Operators can independently validate some parameters and conduct maintenance work to keep the instrument running optimally.

Sensors

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

FRM/FEM instruments

Sensors

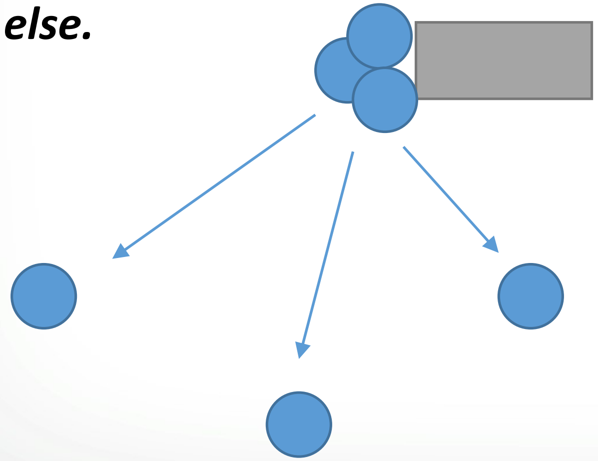


Understanding Sensor Performance

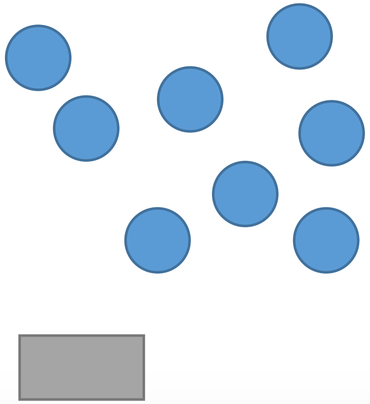
A variety of strategies to overcome sensor performance issues are in development.

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

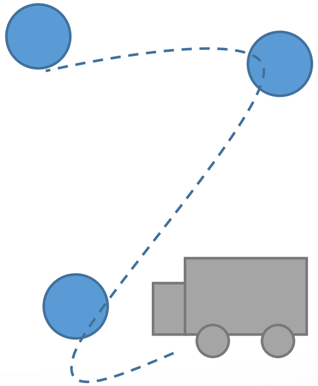
<u>Training approach:</u>
Collocate with reference for a while, then redeploy somewhere else.



<u>Network approach:</u>
Compare/correct between neighboring sites.

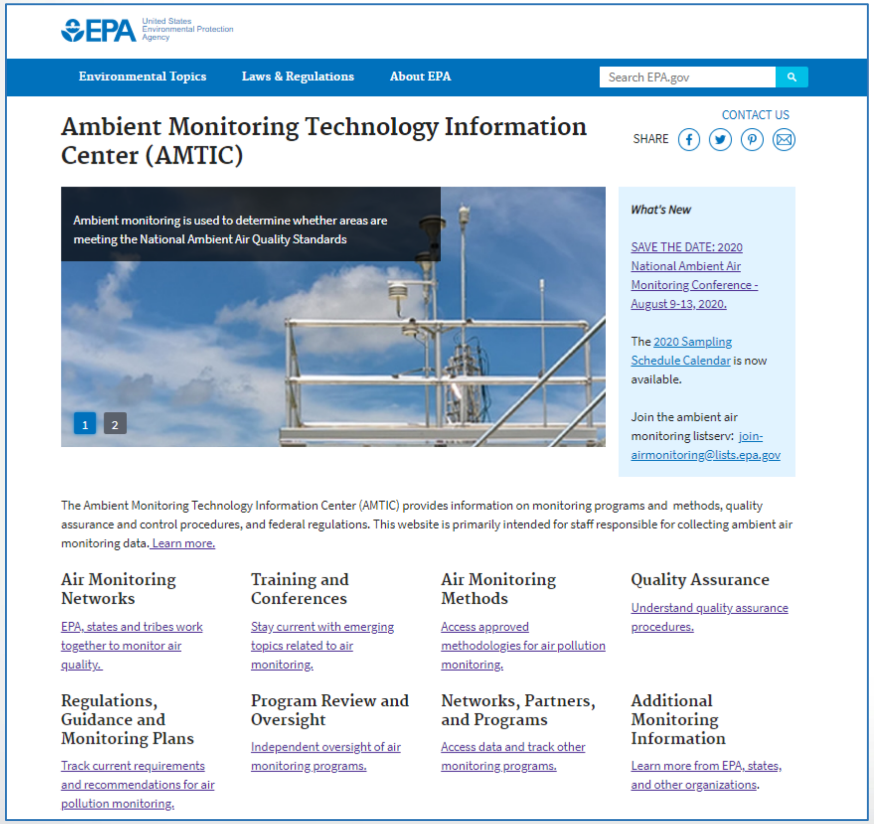


<u>Network with mobile reference</u>:
Drive-by calibration of network.

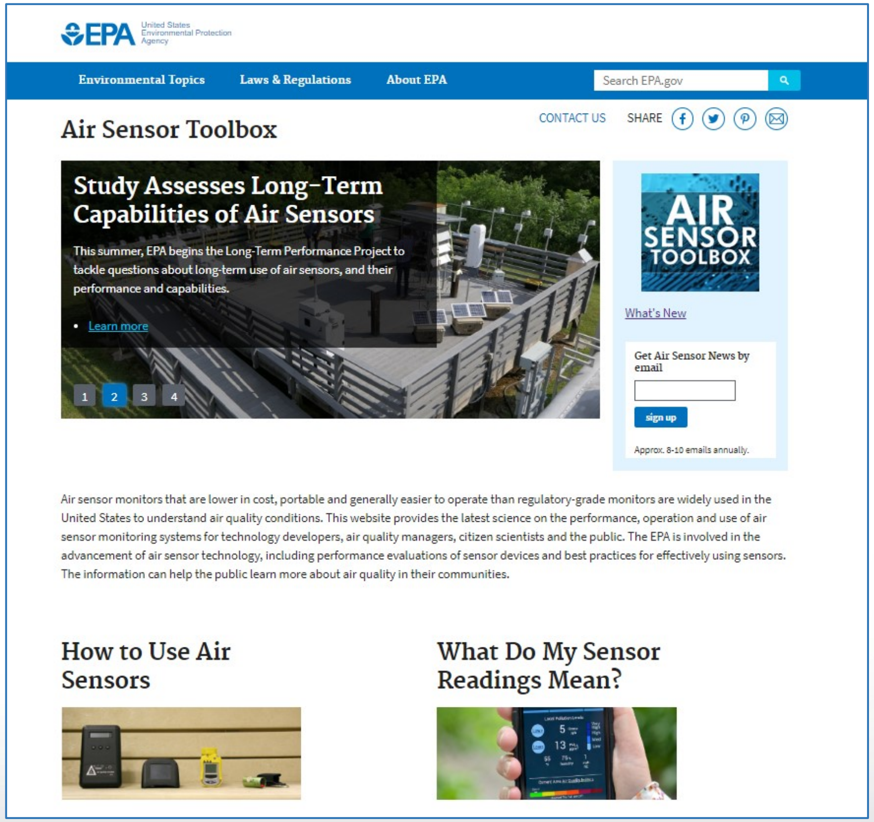


Resources

Ambient Monitoring Technology Information Center (AMTIC) – Learn more about U.S. EPA FRM/FEM instruments and quality assurance and control procedures: www.epa.gov/amtic



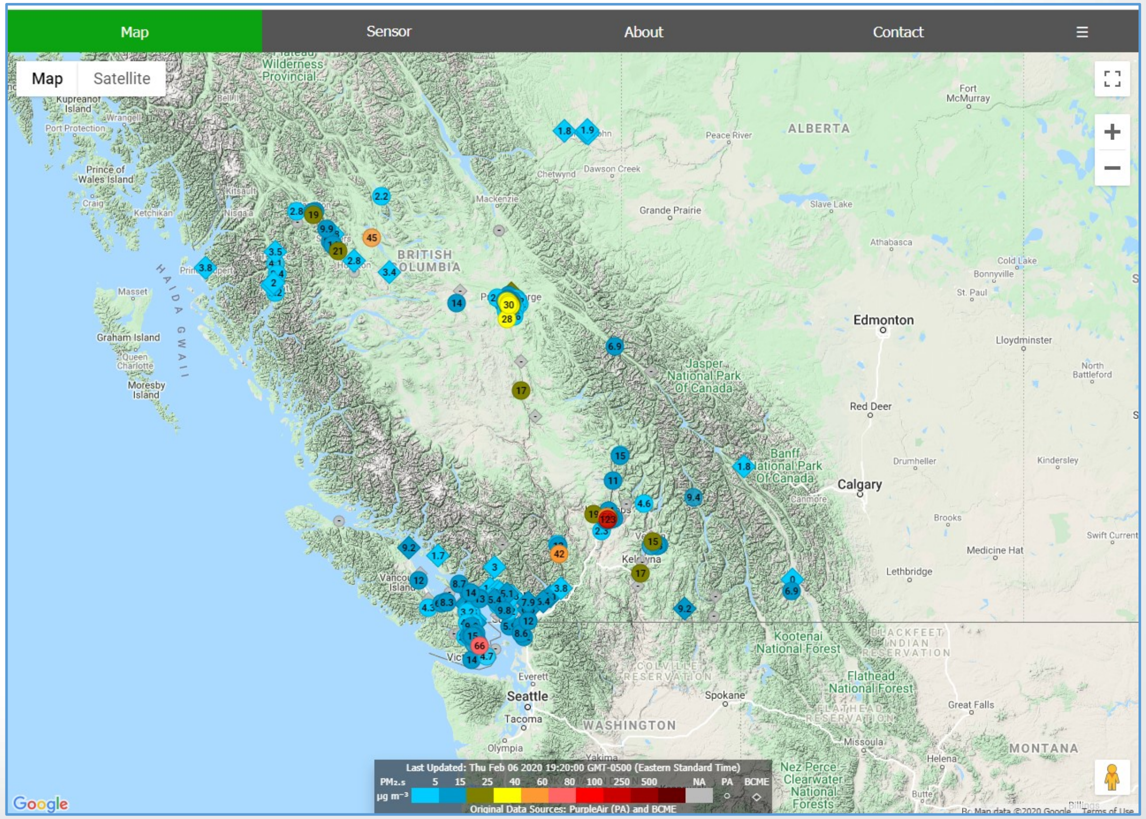
Air Sensor Toolbox – Find guides, resources, performance evaluations, and information about ongoing research involving air sensors: www.epa.gov/air-sensor-toolbox



Resources

Air Quality Sensor Performance Evaluation Center (AQ-SPEC) – Find sensor performance evaluations conducted by California's South Coast AQMD program: www.aqmd.gov/aq-spec

View data from a network of PurpleAir sensors and regulatory monitors (regulatory data from Metro Vancouver and the BC Ministry of Environment and Climate Change Strategy): cirrus.unbc.ca/aqmap/



Questions and Thank You

Thank you!

<u>Contact Info:</u>

Andrea L. Clements, Ph.D.

U.S. EPA Office of Research and Development

clements.andrea@epa.gov