# *Low-cost sensors (LCS) for monitoring air quality*

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*EANET Seminar on expanding monitoring systems using low-cost sensors*

*EANET Project Activity 5 in 2022*

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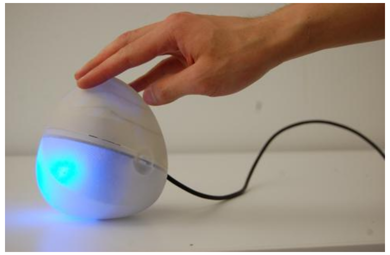
# Outline

- Overview of air sensors
- How are air sensors being used?
- US EPA position on use of air sensors
- US EPA reports on ozone & $PM_{2.5}$ air sensors
- $PM_{2.5}$ air sensors
  - Air sensor testing protocols (field and lab)
  - Base testing: site selection criteria
  - Air sensor setup at testing site
  - Air sensor performance metrics
  - Out-of-box sensor performance
- Comparing $PM_{2.5}$ sensor and FRM/FEM data
- Case Study – US EPA use of $PM_{2.5}$ air sensors to monitor wildfires
  - Developing a correction equation

**Sensor Technologies**

- AirBeam2 Sensors (paired with Android phones)
- PurpleAir Sensors

# Overview of air sensors



- Air sensors (or LCS) are devices that integrate hardware and software and use <u>sensing components</u> to detect or measure pollutants.
- Pollutants monitored using LCS:
  - ***$PM_{2.5}$:*** fairly reliable with collocation; cross-sensitivities, especially to humidity
  - ***Black carbon*** (a key constituent of $PM_{2.5}$); can combine PM LCS with aethalometer
  - ***Ozone ($O_3$):*** fairly accurate, reliable with collocation
  - ***Nitrogen dioxide ($NO_2$):*** highly variable performance, strong cross-sensitivities
  - ***Carbon monoxide (CO):*** fairly reliable with collocation, finite lifetime
  - ***Sulfur dioxide ($SO_2$)****:* highly variable performance; cross-sensitivities, especially to meteorology
  - ***Total Volatile Organic Compounds (tVOC):*** high detection limits, non-speciated measurement

Note: Gas-phase sensors have limited life span (6 mo to 2 years); PM sensors have longer lifespans (3-5 years)

# $PM_{2.5}$ sensing components

Most PM2.5 sensors use optical detection:

- Measures light scattered by particles carried in an air stream through a light beam.
- Composed of a light source (light emitting diode), a light receptor (photodiode detector), a set of focusing lenses, and a fan enclosed in a small housing.

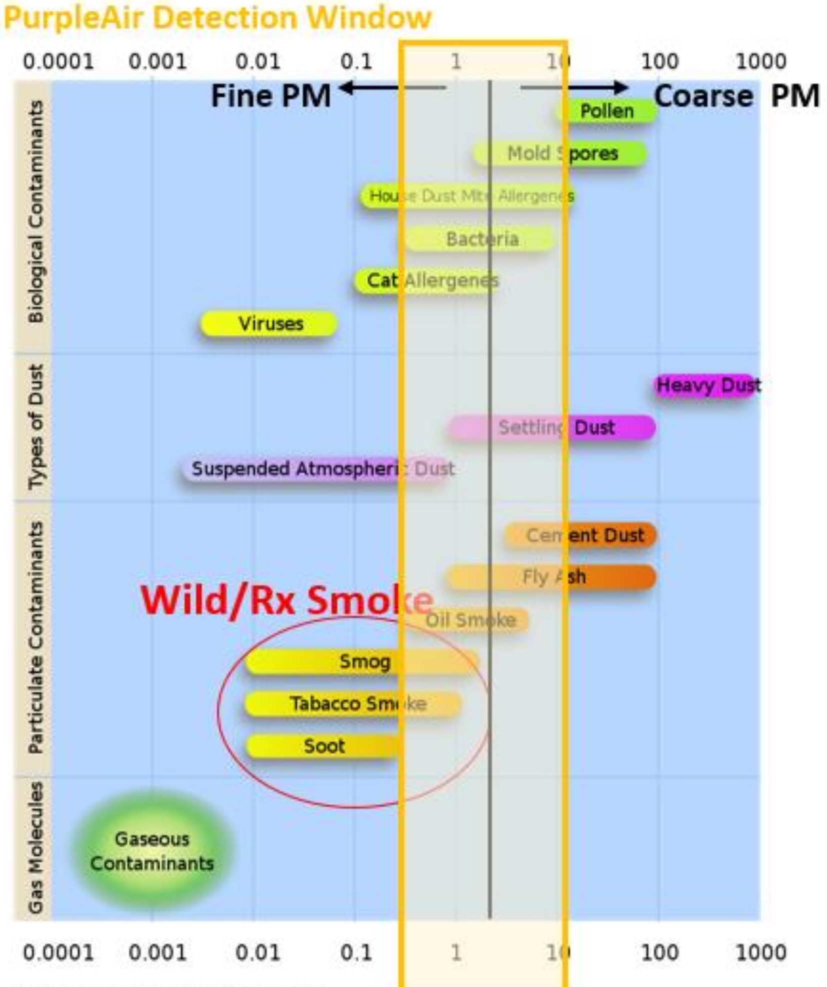



*Image source: Wikipedia*

*Image source: Wikipedia*

# Overview of air sensors

- Compared to Federal Reference or Equivalent Method Monitors (FRMs/FEMs), LCS are smaller, cheaper, and easier to use: $100 to $2500 compared to $20,000+ for a regulatory station.
- US EPA does not accept sensor data as official data, but these data are useful for non-regulatory, supplemental, and informational monitoring (NSIM) applications.

# How are air sensors being used?

- To detect elevated PM events or “hot-spots” (e.g., wood smoke in valleys)
- To improve the spatiotemporal resolution of PM data in widely dispersed sensor networks
- To obtain personalized health information, especially for susceptible people (e.g., asthmatics)
- To raise awareness and educate communities about air pollution, and to inspire behavioral changes
- To supplement national, state, or local monitoring networks (e.g., western US wildfires)
- To identify pollution sources by monitoring near suspected sources
- To locate leaks at industrial facilities
- To assist with daily forecasting
- Air-modeling verification
- To site regulatory monitors
- As a research tool (e.g., epidemiological studies)
- Science education

## NSIM Categories and Specific Examples (adapted from U.S. EPA, 2018)

| Category | Definition | Examples |
|---|---|---|
| Spatiotemporal Variability | Characterizing a pollutant concentration over a geographic area and/or time | Daily trends, gradient studies, air quality forecasting, citizen science, education |
| Comparison | Analysis of differences and/or similarities in air pollution characteristics against a threshold value or between different networks, locations, regions, time periods, etc. | Hot-spot detection, data fusion, emergency response, supplemental monitoring |
| Long-term Trend | Change in a pollutant concentration over a period of (typically) years | Long-term changes, epidemiological studies, model verification |

Taiwan example of using data fusion to improve spatial-temporal resolution of PM2.5 estimates using sensors: https://www.sciencedirect.com/science/article/pii/S0160412018326552

# US EPA position on use of air-sensors

June 2020 - Memo on EPA's position on the use of air sensor data

- Under the Clean Air Act, for compliance with NAAQS, monitoring instruments need to meet sampling, siting, and QA requirements of CFR Parts of Title 40 (40 CFR Parts 50, 53, and 58).
  - Part 50 — National Primary and Secondary Ambient Air Quality Standards (NAAQS) https://ecfr.io/Title-40/Part-50
  - Part 53 - Ambient Air Monitoring Reference and Equivalent Methods https://ecfr.io/Title-40/Part-53
  - Part 58 - Ambient Air Quality Surveillance https://ecfr.io/Title-40/Part-58
- Sensors are not likely to meet these requirements. However, they provide useful information for many non-regulatory supplemental and informational monitoring (NSIM) applications
- For NSIM applications, there is a need to assess uncertainty and ensure that devices are adequate for intended purposes (identify pollution hotspots, monitor in new areas, build community AQ awareness, etc.)

# US EPA position on use of air-sensors

- Key areas of focus for air sensors: data quality, data interpretation, and data management
- Challenges:
  - Ability to accurately and precisely measure pollutant of interest (i.e., ability to meet data-quality performance indicators or data quality objectives (DQOs)).
  - Performance under different environmental conditions (effects of RH, temperature, different pollutant types/concentrations).
  - Ability to measure target pollutants in a pollutant mixture.
  - Performance out-of-the-box:  Are corrections/adjustments needed to provide more accurate data?
  - Performance over time
  - How to interpret short-term values
- Sensor data uncertainties result in distrust of data, data disregarded based on quality issues, loss of public confidence in decision-makers.

# US EPA position on use of air-sensors

- To characterize LCS measurements, EPA is supporting research on sensor performance including:
    - Development of non-regulatory performance targets and testing protocols for monitoring applications that complement – but do not replace – existing regulatory programs.
    - Interpretation of real-time, non-regulatory LCS data
- EPA recognizes need for guidance related to interpretation and communication of LCS data.
    - For example, sensor data may show episodic spikes in pollutant concentrations, but health science doesn't tell us what short-term (e.g., one minute) exposures mean for an individual.

# US EPA example of communicating sensor data (analogous to AQI)

**Pilot Version 1-minute particle pollution (PM2.5) readings (Not for regulatory purposes)**

| Pilot Scales | Message |
|---|---|
| Low<br>0-29 µg/m3 | Enjoy your outdoor activities. |
| Medium<br>30-69 µg/m3 | If medium readings continue (for an hour or more), use the Air Quality Index to plan outdoor activites. |
| High<br>70-499 µg/m3 | You may be near a source of particle pollution like dust, smoke or exhaust. Check the air Quality Index to plan outdoor activities. |
| Very High<br>>=500 µg/m3 | You may be near a source of particle pollution like dust, smoke or exhaust. Check the Air Quality Index to find out if you should adjust outdoor activities. Very high readings may mean the sensor is not working properly. |
| 🔧 | Sensor may be offline. Check the Air Quality Index. |

Low
0-29 µg/m3

Medium
30-69 µg/m3

High
70 - 499 µg/m3

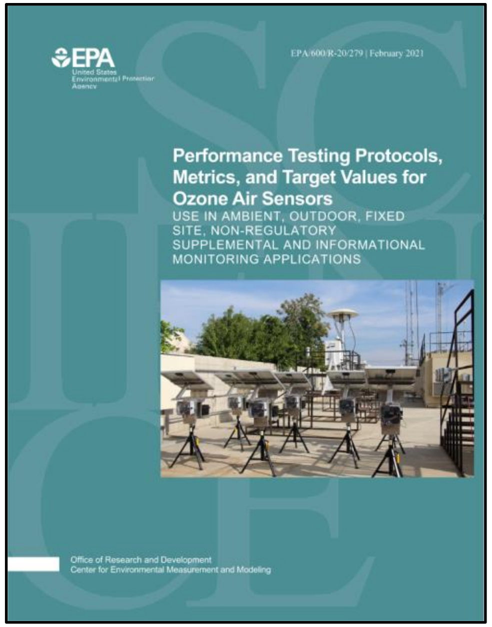
Very High
≥500 µg/m3

🔧

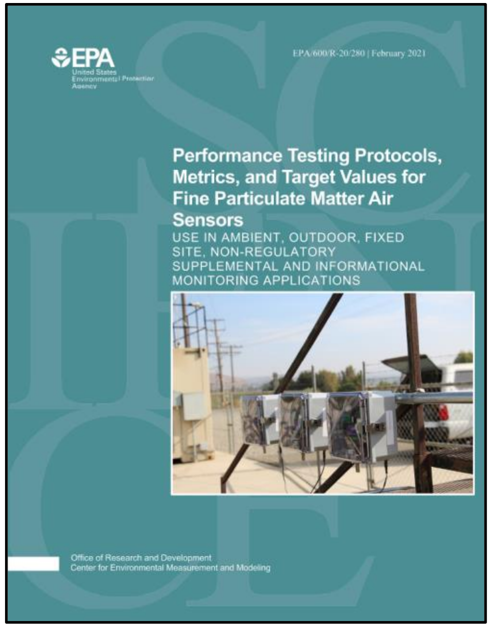
| Air Quality Index Levels of Health Concern | Numerical Value | Meaning |
|---|---|---|
| Good | 0 to 50 | Air quality is considered satisfactory, and air pollution poses little or no risk |
| Moderate | 51 to 100 | Air quality is acceptable; however, for some pollutants there may be a moderate health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

# US EPA reports on ozone & $PM_{2.5}$ air sensors

- **Intended audience**: testing organizations, sensor developers, sensor manufacturers
- **Goal**: to provide consistent approach for performance testing and for reporting results to help users identify sensors that meet their needs.
- **Testing protocols** are specifically for ambient, outdoor, fixed-site environments and for non-regulatory supplemental and informational monitoring (NSIM) applications




Ozone: EPA/600/R-20/279
Feb 2021




$PM_{2.5}$: EPA/600/R-20/280
Feb 2021

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

Note: similar reports with same NSIM application focus of sensors for other pollutants ($PM_{10}$, $NO_2$, CO, $SO_2$ ) are being developed.

# US EPA reports on ozone & $PM_{2.5}$ air-sensors

Focus and approach:

- Review of peer-reviewed literature focusing on:
  - Performance attributes (e.g., measurement range, detection limit)
  - Metrics [e.g., precision (SD or CV), bias (slope, intercept)]
  - Testing protocols [base (field) testing, enhanced (lab) testing]
- EPA and ECOS (Environmental Council of the States) hosted a workshop "Air Sensors 2018: Deliberating Performance Targets" with 700 in attendance, including experts from government, academia, and international organizations and stakeholders from states, tribes, sensor manufacturers, general public.

https://www.epa.gov/sites/default/files/2018-10/documents/epareshighlights-em_published_-_air_sensors.pdf
https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=344961&Lab=NERL
https://www.epa.gov/air-research/presentations-deliberating-performance-targets-air-quality-sensors-workshop-june-25-27

# Air sensor testing protocols (field and lab)

- EPA encourages testers to conduct base testing at a minimum.
- EPA also encourages enhanced testing, but it requires a controlled lab exposure chamber.

**Recommended Testing Protocols for Understanding $PM_{2.5}$ Air Sensor Performance**

| Test Type | Setting | Description | Purpose |
|---|---|---|---|
| Base Testing | Field | Consists of field deployments of at least three replicate $PM_{2.5}$ air sensors with collocated FRM/FEM monitors for a minimum of 30 days each, at two test sites within different climate regions. | Provides information on sensor performance that is relevant to real-world, ambient, outdoor conditions.<br><br>Allows consumers to predict how a sensor might perform in similar conditions. |
| Enhanced Testing | Laboratory | Consists of testing at least three replicate $PM_{2.5}$ air sensors in controlled laboratory conditions to understand the effect of temperature and relative humidity; drift; and accuracy at higher concentration levels. | Allows for evaluation of sensors over a range of conditions that may be challenging to capture in the field.<br><br>Characterizes certain performance parameters that are difficult to test in the field. |

# Base testing: site selection criteria

**Test Site Selection Criteria**

| Base Testing Plan | Location(s) | Season | Goal 24-Hour Average $PM_{2.5}$ Concentration (for at least one day) |
|---|---|---|---|
| Two test sites | Site 1 | Climate Region 1 | $\geq 25\ \mu g/m^3$ |
| | Site 2 | Climate Region 2 | $\geq 25\ \mu g/m^3$ |

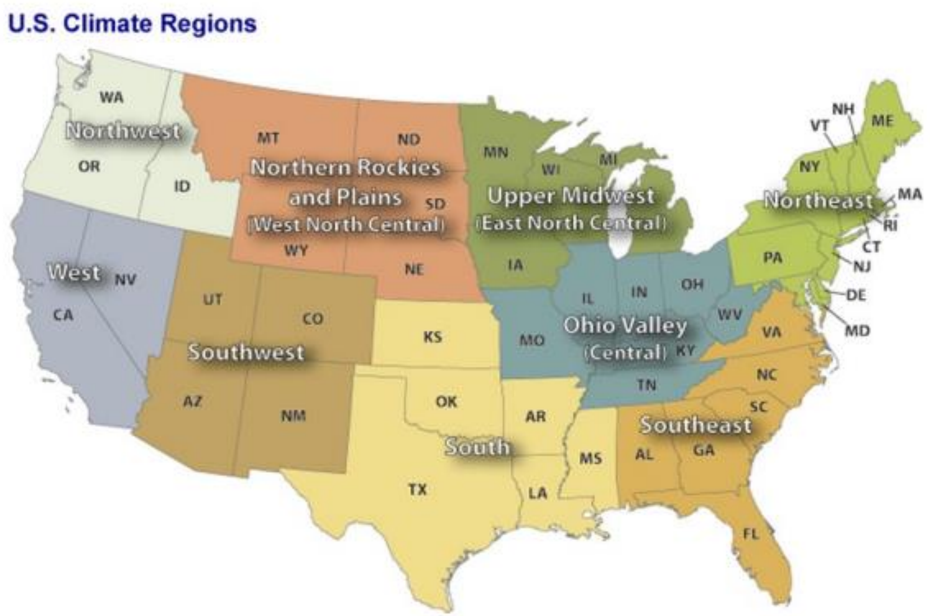



**Figure 2-2. U.S. Climate Regions (https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php, *last accessed 07/29/2020*)**

# Air sensor setup at testing site

| Recommendations | Cautions |
| --- | --- |
| • Mount sensors within 20 meters horizontal of the FRM/FEM monitor<br>• Mount sensors in a location where they are exposed to unrestricted air flow<br>• Ensure the air sampling inlet for the sensors are within a height of ± 1 meter vertically of the air sampling inlet of the FRM/FEM monitor<br>• Mount identical sensors ~1 meter apart from each other<br>• If necessary, install sensors within a weather-protective shelter/enclosure that maintains ample air flow around the sensor (as recommended by manufacturer) | • Do not place sensors near structures/objects that can affect air flow to the sensor OR block the sensor air intake (e.g., against a wall, near a vent, or on the ground blocking the inlet)<br>• Do not place sensors near structures/objects that can alter T or RH near the sensor (e.g., vents, exhausts)<br>• Do not place sensors near sources/sinks that can alter pollutant concentrations (e.g., idling cars, smoking)<br>• Do not place sensors in locations with risk of vibration, electrical shock, or other potential hazards |

EPA

## Sensor Performance Parameters

Accuracy (bias), stability over time, temperature, averaging time

Linearity (including saturation)

$R^2$ (if appropriate), RMSD, other? – averaging time

Precision (in-motion degradation?), bias corrected precision?

Sensitivity / LOD (as a function of averaging time)

Baseline stability (with time / temperature)
- Important at low end of sensor range
- Can be driver of data quality at ambient concentrations

Interferences Can be data quality driver!

Values for these parameters depend on
- type of sensor, pollutant
- performance tier / DQOs
- averaging time of interest

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

NO scavenging of ozone by "titration" often occurs near busy roads and in power-plant plumes.

Example: Electrochemical O3 sensor – NO2 interference
- Can have 1:1 response with NO2
- In urban air, NO2 is higher and O3 is lower (NO scavenging)
- Result: large positive error for O3

Example: PM Sensor – RH interference
- Ambient tests in semi-arid climate (western US) may not reflect performance in humid climate (eastern US)
- Useful to know if a sensor measures and reports RH (and corrects data for it?)

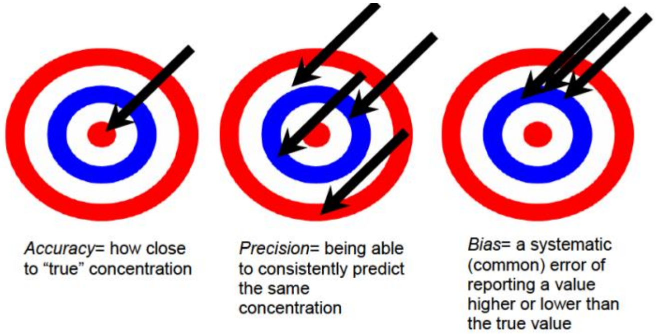
From G. Allen, "Is it good enough?" The Role of PM and Ozone Sensor Testing/Certification Programs
https://www.epa.gov/air-research/presentations-deliberating-performance-targets-air-quality-sensors-workshop-june-25-27

# Air sensor performance metrics

**Base and Enhanced Testing – Recommended Performance Metrics and Target Values for $PM_{2.5}$ Air Sensors**

| Performance Metric | | Target Value: Base Testing | Target Value: Enhanced Testing* |
|---|---|---|---|
| Precision | Standard Deviation (SD) | $\leq 5\ \mu g/m^3$ | No target values recommended; report results |
| | -OR- | | |
| | Coefficient of Variation (CV) | $\leq 30\%$ | |
| Bias | Slope | $1.0 \pm 0.35$ | |
| | Intercept (b) | $-5 \leq b \leq 5\ \mu g/m^3$ | |
| Linearity | Coefficient of Determination ($R^2$) | $\geq 0.70$ | |
| Error | Root Mean Square Error (RMSE) or Normalized Root Mean Square Error (NRMSE) | RMSE $\leq 7\ \mu g/m^3$ or NRMSE $\leq 30\%$† | |

*No specific target values are recommended due to limited feasibility, lack of consensus regarding testing protocols, and inconsistency in sensor evaluation results that can result from the limited amount of data that will be collected and variation in the tester's choice of PM surrogate. See Appendix D for further discussion.



# Out-of-box sensor performance metrics (before user corrections)

**$PM_{2.5}$ Sensor Performance Field Evaluation Results from Available Resources**

| Performance Metric | | Range | Average | Median |
|---|---|---|---|---|
| Precision | CV (%) | 0.89 to 31.03 | 12.78 | 11.62 |
| Bias | Slope* | 0.50 to 1.49 | 1.09 | 1.12 |
| | Intercept* (µg/m³) | -19.08 to 0.91 | -3.75 | -3.19 |
| Linearity | $R^{2, \dagger}$ | 0.52 to 0.97 | 0.80 | 0.83 |
| Error | RMSE (µg/m³) | 2.41 to 7.64 | 5.28 | 5.52 |

Note: Resources include AQ-SPEC sensor evaluations, the U.S. EPA sensor evaluations, and peer-reviewed literature. Table only includes 24-hour averaged data.

## Possible Tier Descriptors

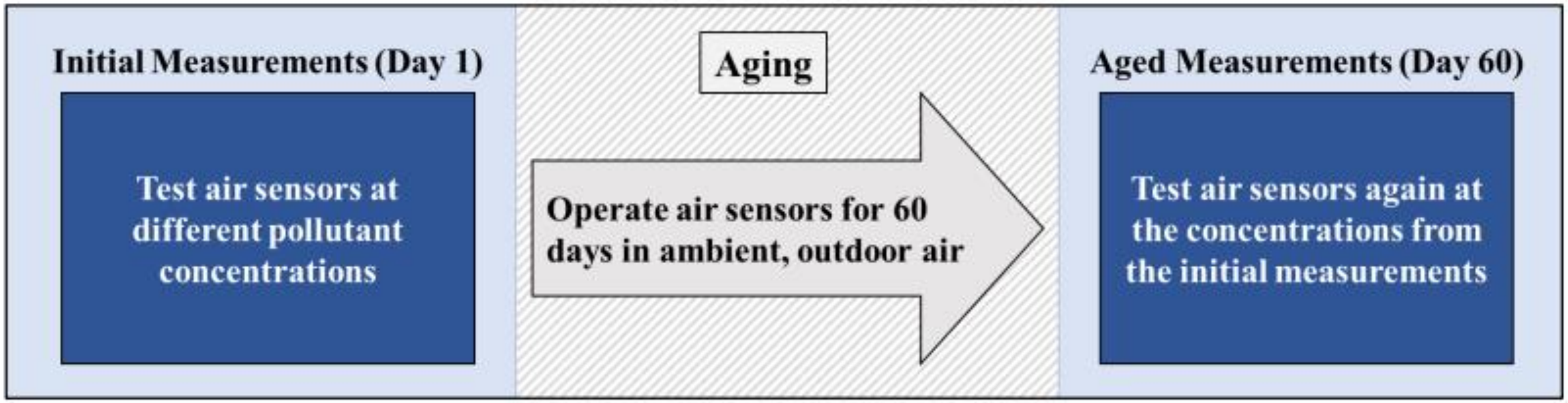
| | | |
|---|---|---|
| 0. Just don't use it: | $R^2 < 0.25$ ..or.. | RMSD > 100% |
| 1. Qualitative: | $R^2$ 0.25 to 0.50, | RMSD < 100% |
| 2. Semi-quantitative: | $R^2$ 0.50 to .75, | RMSD <50%, bias < 50% |
| 3. Reasonably quantitative: | $R^2$ 0.75 to .90, | RMSD <20%, bias <30% |
| 4. Almost regulatory quality: | $R^2$ >.90, | RMSD <10%, bias < 15% |

Example for PM2.5: Thermo pDR1500 (EPA Village Green PM)

Need to specify averaging time.

From G. Allen, "Is it good enough?" The Role of PM and Ozone Sensor Testing/Certification Programs
https://www.epa.gov/air-research/presentations-deliberating-performance-targets-air-quality-sensors-workshop-june-25-27

# Drift testing




**Drift Testing to Determine Changes After 60 days or More of Continuous Operation**

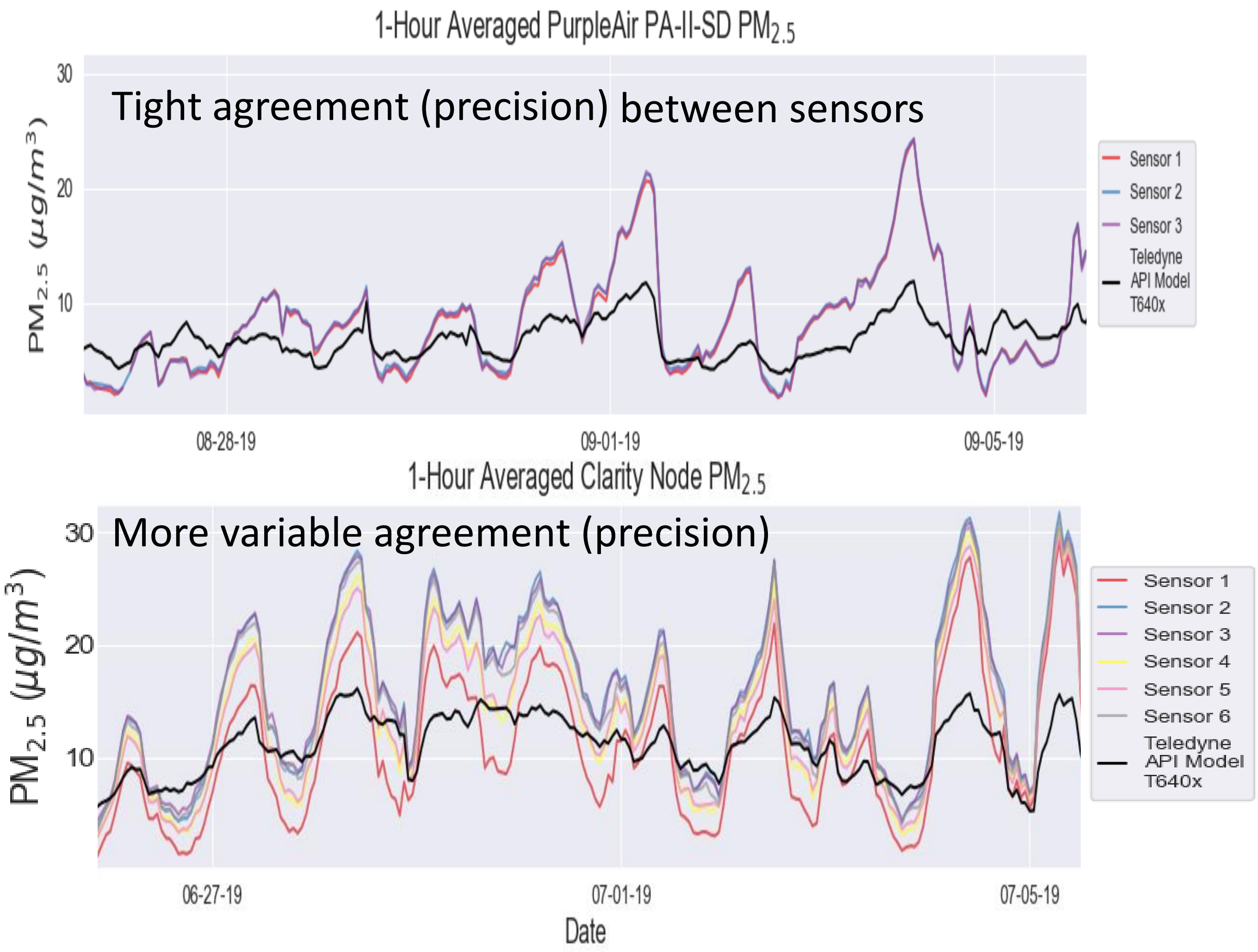
- For low (e.g., 10 µg/m3) to mid (35 µg/m3) $PM_{2.5}$ concentrations, operate sensors in ambient, outdoor air.
- For high (e.g., 150 µg/m3) $PM_{2.5}$ concentrations, recommend using exposure chamber.

## Table D-2. Summary of U.S. EPA $PM_{2.5}$ Sensor Evaluation Field Results (24-hour Average)

| Sensor Manufacturer/ Model | Sensor Concentration Range (µg/m³) | Reference Concentration Range (µg/m³) | Precision (CV, %) | Slope* | Intercept* (µg/m³) | $R^{2,*}$ | RMSE (µg/m³) |
|---|---|---|---|---|---|---|---|
| Aeroqual/AQY | 1-12 | 4-15 | 15.32† | 0.61 (0.42 to 0.87) | -0.99 (-2.0 to -0.19) | 0.77 (0.70 to 0.89) | 4.52 |
| AirVisual/ AirVisual Pro | 1-16 | 3-21 | 16.90 | 0.95 (0.88 to 1.07) | -1.51 (-1.81 to -1.19) | 0.82 (0.65 to 0.91) | 2.41 |
| Airviz/Speck v2 | 0-25 | | | -6.54 | 119.11 | 0.03 | |
| APT/Maxima | 1-24 | 3-16 | 9.91 | 1.83 (1.69 to 1.96) | -7.72 (-.823 to -6.42) | 0.89 (0.87 to 0.95) | 3.50 |
| Cairpol/CairClip PM Prototype | 0-25 | | | -0.01 | 0.13 | 0.01 | |
| Clarity/Node | 2-21 | 5-15 | 13.32 | 1.84 (1.42 to 2.07) | -5.94 (-6.84 to -4.69) | 0.84 (0.76 to 0.88) | 3.59 |
| Clarity/Node-S | 3-27 | 5-15 | 4.62 | 2.28 (2.18 to 2.38) | -5.38 (-5.62 to -5.12) | 0.77 (0.75 to 0.79) | 7.64 |
| Dylos/DC 1100 | 0-30 | | | | | 0.42 (0.40 to 0.46) | |
| HabitatMap/AirBeam | 0-30 | | | | | 0.47 (0.45 to 0.48) | |
| [illegible] | [illegible] | | | 0.30 | 0.15 | 0.17 | |

Table continues ….

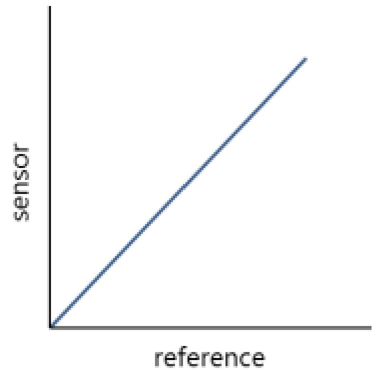
# $PM_{2.5}$ air sensors: examples of bias, lack of precision



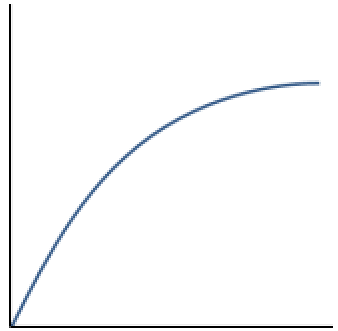

- Sensors and regulatory monitors may capture the general pattern of $PM_{2.5}$. However, absolute concentrations may be biased high or low.
- There may be significant variation in agreement (or precision) between sensors of same make and model. Data corrections may be needed to compare data from two similar sensors

# Comparing $PM_{2.5}$ sensor and FRM/FEM data

- Linear corrections may be suitable at lower ambient concentrations (common in U.S.)
- The relationship between sensor and FRM/FEM measurements may change depending on concentration
- Shifts in aerosol properties (e.g., seasonal dust source) often changes the relationship between sensor and FRM/FEM reference measurements



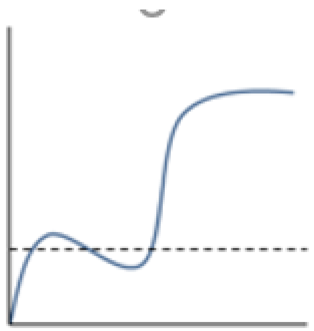

Ideal



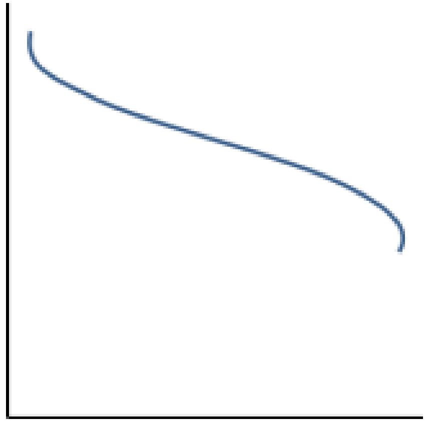
Curved, but the sensor output becomes constant even though reference concentrations are still increasing.

Air Sensor Guidebook (clickable link)

# Comparing $PM_{2.5}$ sensor and FRM/FEM data



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



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

# Case Study – US EPA use of air sensors to monitor US Wildfires

- For wildfire smoke monitoring, supplemental data are needed due to spatial variability of smoke impacts and sparse FRM/FEM monitoring network.
- In 2020, EPA partnered with state, tribal and local air-monitoring groups and US Forest Service to add sensor data to the AirNow Fire and Smoke Map.
- Goal to develop a single model to be applied to all crowd-sourced PurpleAir $PM_{2.5}$ data.

- **Purple Air sensors**
  - Widely used by public
  - Evaluations reveal that data is often biased high
  - Identified need for correction equation for Purple air $PM_{2.5}$ sensor data to address bias.
  - Correction allowed 1000s of new AQ observations to be added to map and visualized at the same scale.

*Image source: http://nwcg.gov*

# Field Testing of PurpleAir sensors

**Sensors were collocated with FRM, FEM, or temporary monitors across the country**

- Typical ambient conditions were sampled in several NOAA climate regions over several seasons with help from state/local/tribal agency partners
- Smoke-impacted conditions were sampled from fresh and aged prescribed burns and wildfire burns with several fuel types
- Higher concentrations were sampled from several locations during 2020 wildfires


Regions and state, local, and tribal air-monitoring sites with collocated PurpleAir sensors used to evaluate correction model.

# Selected correction model

- Removed poorly performing sensors and short-term outlier measurements using channel A and B comparisons.
- The US correction improves PurpleAir performance, reducing 24-h averaged $PM_{2.5}$ data RMSE from 8 to 3 µg $m^{-3}$ when evaluated against regulatory measurements across US, and reduced bias to ±3 µg $m^{-3}$ when validated on a state-by-state basis and to ±1 µg $m^{-3}$ when evaluating by region.
- Only an RH correction needed to reduce error and bias in the nationwide dataset.

  $$PM2.5 = 0.524 \times PAcf\_1 - 0.0862 \times RH + 5.75$$

- More work needed to understand if similar corrections can be developed for other sensor types.

PM2.5= µg m-3 • RH= Relative Humidity (%) • PA_cf1(avgAB)] =PurpleAir higher correction factor data averaged from the A and B channels

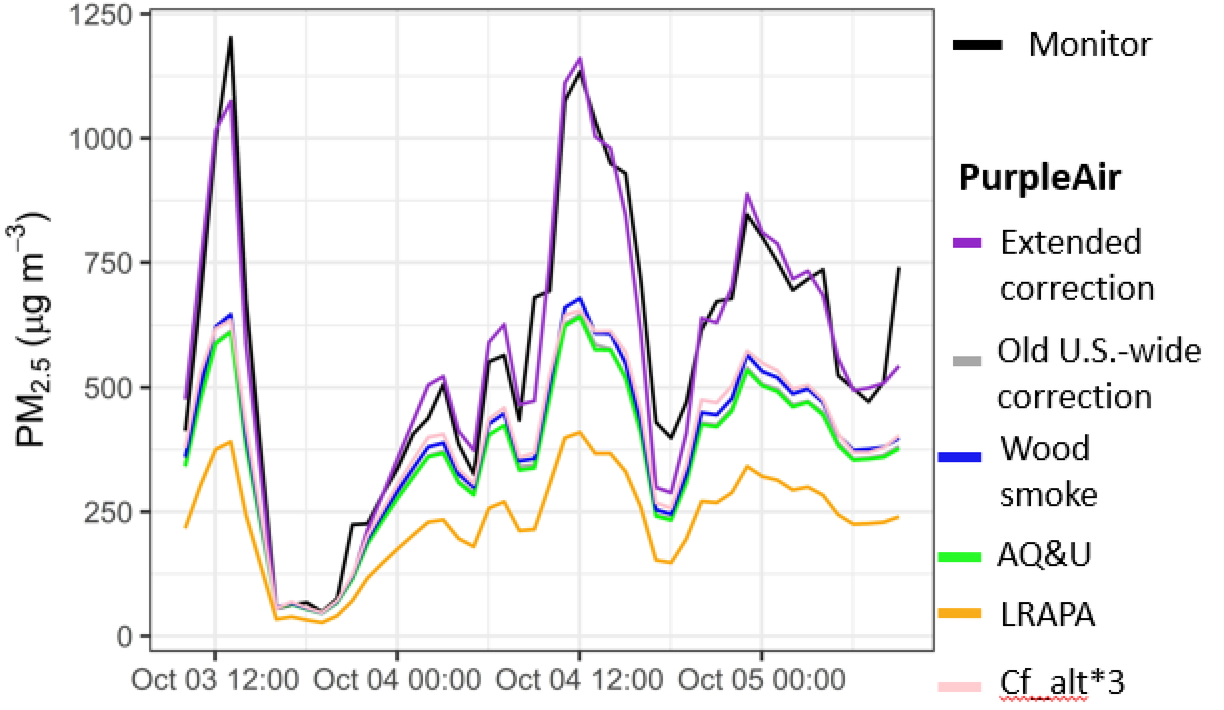
Barkjohn et al. 2021, https://doi.org/10.5194/amt-14-4617-2021
Holder et al. 2020, https://doi.org/10.3390/s20174796

# Improved $PM_{2.5}$ estimates

US-wide correction yields better agreement between sensor and reference monitors

- Better agreement over full range of concentrations
- Evaluation at AQI breakpoint suggests the bias ≤±8% and error ≤± 20%

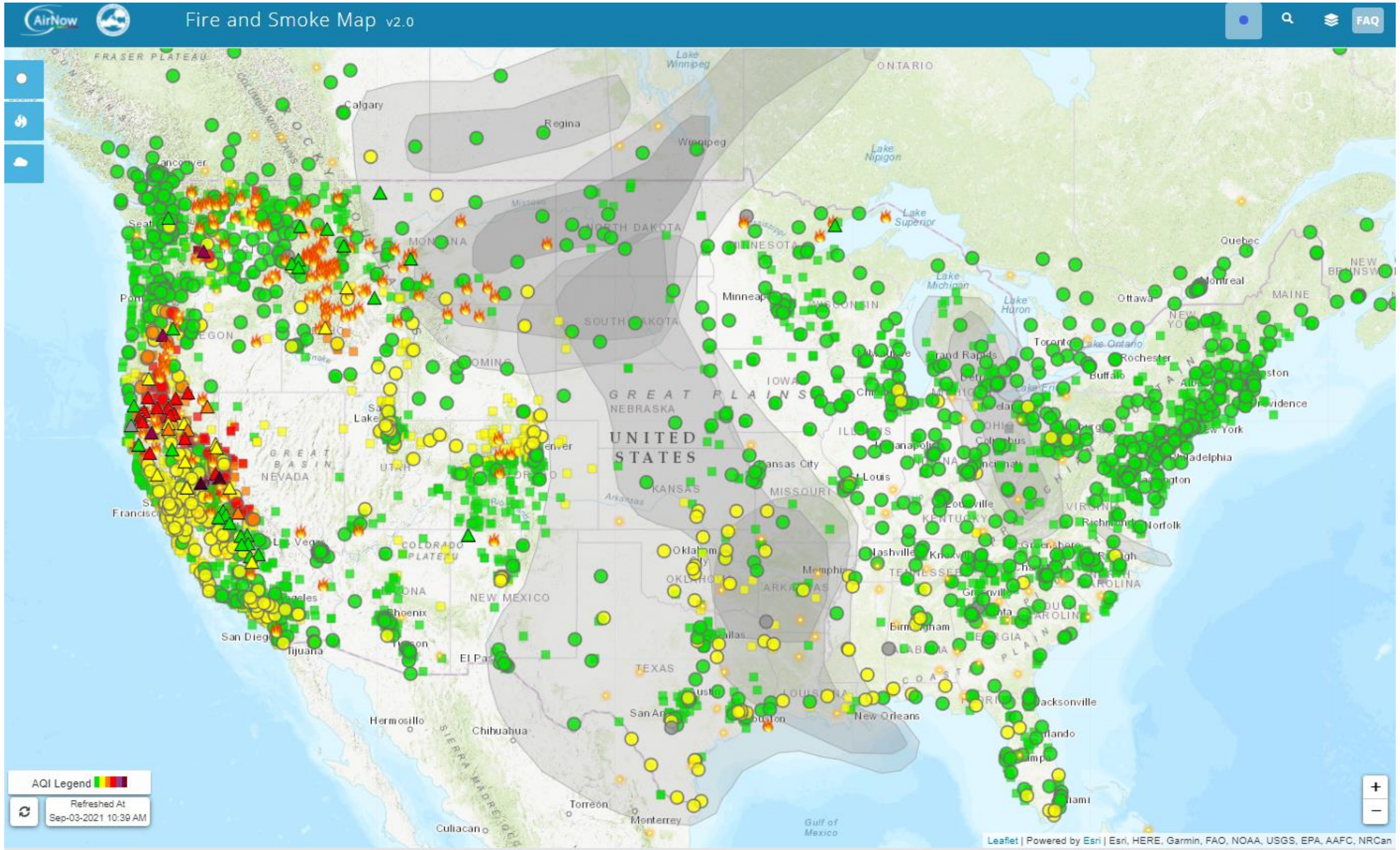
Example: 1-hr 2020 averaged data from Forks of Salmon (CA)




[1]Cf_alt*3 may soon be added. Details: https://doi.org/10.1016/j.atmosenv.2021.118432
[2]LRAPA – Lane Regional Air Protection Agency

# Integration of data sources into AirNow fire & smoke map

- Map provides localized data important for communities impacted by smoke
- Map integrates satellite smoke data and fire information



# Contacts

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U.S. EPA Air Sensor Toolbox: https://www.epa.gov/air-sensor-toolbox

Information on US EPA reports on ozone & $PM_{2.5}$ air sensors based on work by US EPA ORD scientists Andrea Clements, PhD clements.andrea@epa.gov and Rachelle Duvall, PhD duvall.rachelle@epa.gov