How to Evaluate Low-Cost Sensors by Collocation with Federal Reference Method Monitors

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Introduction and Objective

Recent technological advances in air quality monitoring are providing smaller, lower-cost, sensor-based monitors.

- These <u>low-cost sensors</u> can measure some of the same air pollutants that more costly <u>reference monitors</u> can measure.

- But how good are they?

The goal of this presentation is to provide instructions for evaluating low-cost sensors by collocating them with reference monitors and comparing measurements of the two to determine the "trustworthiness" of low-cost sensors.

Background: Reference Monitors

What are Reference Monitors? Why do we need them?

- The Clean Air Act requires every state to establish a network of air monitoring stations to monitor criteria air pollutants that must meet National Ambient Air Quality Standards (NAAQS). Not all criteria pollutants are measured at all stations.
- The measurement instruments and methods used at these regulatory monitoring stations are called Federal Reference Methods (FRM) or Federal Equivalent Methods (FEM).

- The FRM/FEM instruments must meet rigorous standards for accuracy and reliability (see 40 CFR part 53 for details). These instruments are "The Gold Standard".
- In this presentation, these FRM/FEM instruments will be referred to as *reference monitors* for simplicity.

Background: Reference Monitors vs Low-Cost Sensors

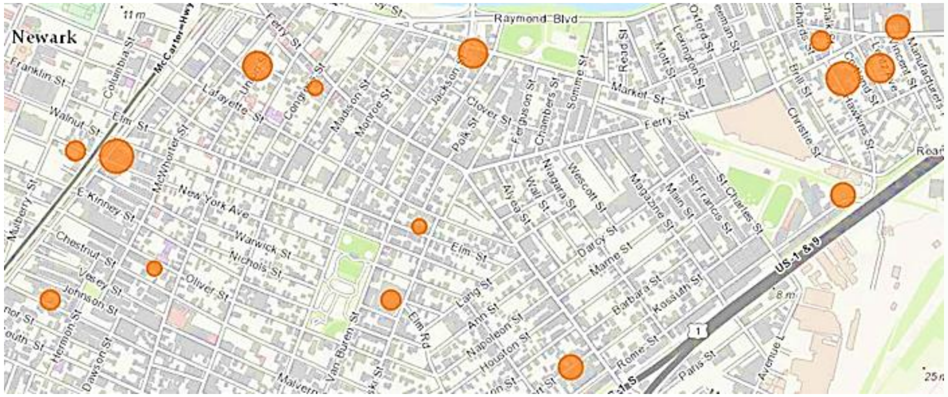
Here is how low-cost sensors compare with reference monitors:

	Reference Monitors	Low-Cost Sensors
Typical Purchase Cost Range	$15,000 to $50,000	$100 to $2500
Operating Expense	Expensive	Inexpensive
Siting Location	Fixed Location (building/trailer needed)	Portable (basic weather shielding)
Staff Training	Highly trained technical staff	Little or No Training
Data Quality	Known and consistent quality in a variety of conditions	Unknown and may vary from sensor to sensor and in different weather conditions
Operating Lifetime	10+ Years (calibrated and operated to maintain accuracy)	Short (1 year) or Unknown (may become less sensitive over time)
Used for Regulatory Monitoring?	Yes	No

Background: Low-Cost Sensors

How can low-cost sensors be used?

- The low-cost and portability of these sensors makes it possible to measure air quality in more locations.
- Many of these sensors can report measurements at a frequency on the order of minutes, or even seconds, making it possible to learn about changes in air quality throughout the day.



Orange dots are sensor monitoring locations in Newark area.

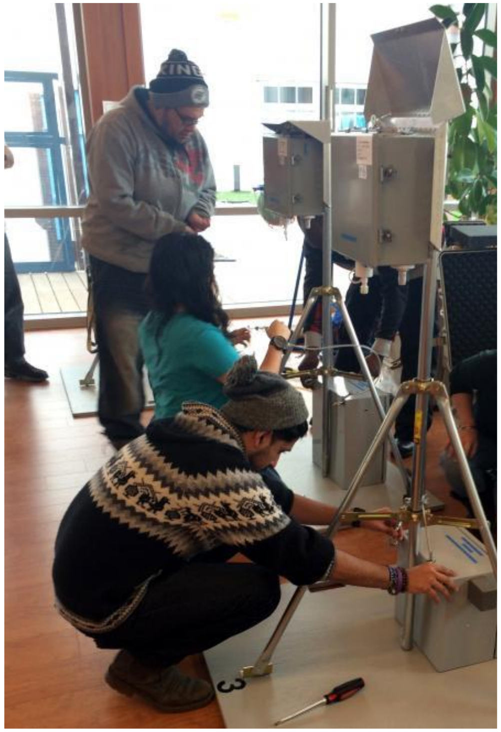
Low-cost sensors may be used to locate pollution hotspots, identify sources of pollution, supplement fixed-site monitoring data, measure personal exposure to pollutants, educate, and enhance air quality awareness.

Background: Low-Cost Sensors

The low cost, portability, and ease of use of sensor technology make it possible for citizens to participate in air quality monitoring within their communities. Here are some examples:

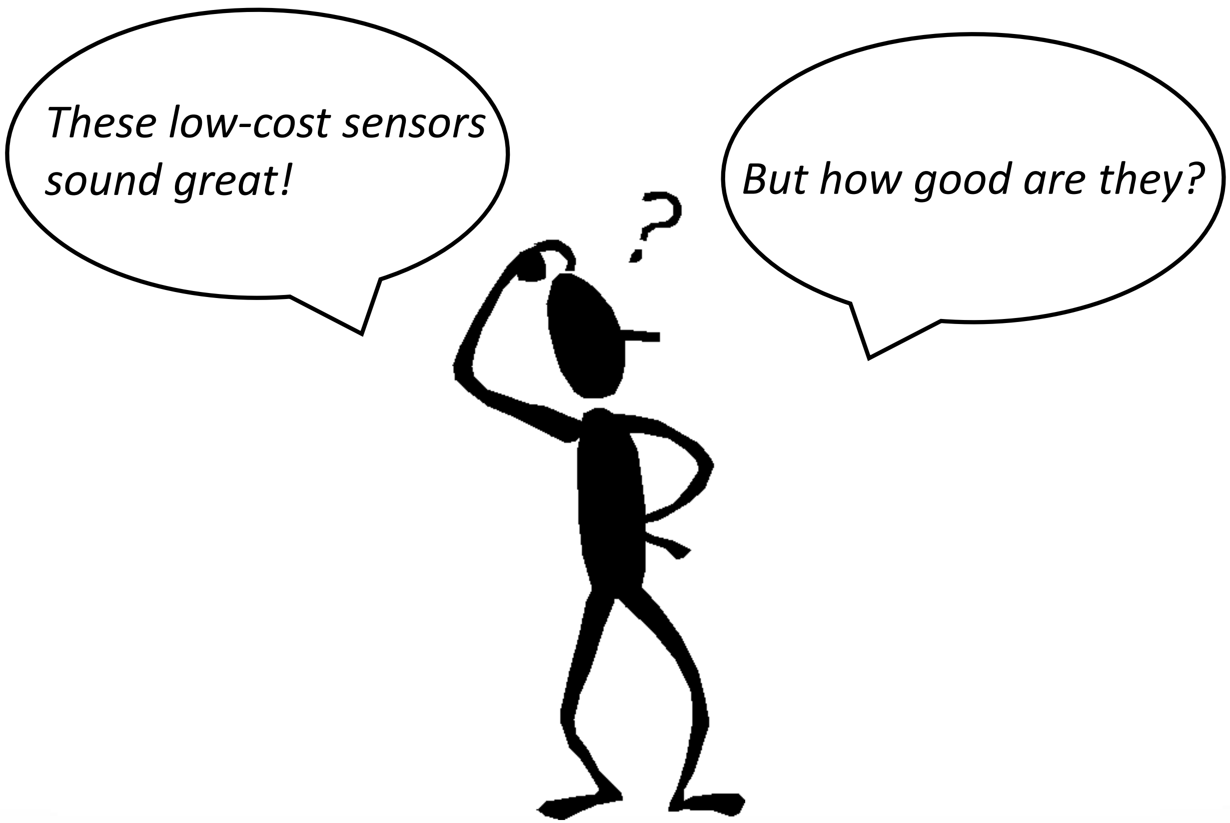
- Ironbound Community, Newark, New Jersey
- DISUR (Desarrollo Integral del Sur), Ponce, Puerto Rico
- Federal Crowdsourcing and Citizen Science Toolkit

EPA and citizens at a monitoring site.



Citizens learning to operate EPA sensor pods.

Background: Low-Cost Sensors



Evaluating Low-Cost Sensors: Collocation

What is collocation?

- **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 and data accuracy improved by comparing sensor data with reference monitor data.
- Here are some examples of sensor evaluations by collocation with reference monitors:
    - Particulate Matter Sensor Evaluation Report
    - Sensor Evaluation Report

More examples of collocation can be found on the Air Sensor Toolbox web page.

Purpose

- The materials provided in this presentation will give you an understanding of the important considerations for any collocation effort.
- The goal of a collocation effort is to evaluate sensor data quality and help answer some important questions like these:

Why are my two sensors saying different things?

Are my sensor readings accurate?

Is this number bad? What does it mean?

Use collocation to help you answer these questions!

Approach

<u>Collocation</u> is a multi-step process.

You can link to each step by clicking in this graphic:

Step 1: Planning

Step 2: Making Measurements

Step 3: Data Recovery and Review

Step 4: Data Comparison

Step 5: Using Sensors

Step 1: Planning a Sensor Evaluation

What sensor are you evaluating?

- If you are planning to evaluate a sensor, you probably have already determined what pollutant you want to measure, and what sensor you want to use to measure it. Keep in mind that not all criteria (regulated) pollutants can be measured with low-cost sensors.
- If not, start by asking a question to get you started – something like "What time of day are particulate matter concentrations highest in my neighborhood?" Think about logistics – the ***who, what, where, when, why, how.***

The Air Sensor Guidebook is a good place to learn about air quality, pollutants, and their sources (chapter 2) and what to look for in a sensor (chapter 3).

Step 1: Planning a Sensor Evaluation

How many sensors do I need?

- If possible, acquire at least 3 units of the same sensor.

Why should I evaluate three (or more!) sensors?

- It will be easier to recognize a faulty sensor.
- You'll have more data to evaluate the accuracy and variability of the sensor measurement.

Example of sensors being tested in triplicate

Step 1: Planning a Sensor Evaluation

Besides sensors, what equipment and supplies do I need?

- ***What power source do I need?***
  - <u>AC power</u>: Make sure you have sufficient numbers and lengths of power cords, and a place to plug everything in.
  - <u>Other</u>: Solar panels/batteries/charging cables
- ***How is the data stored or transmitted?***
  - <u>Storage media</u>: Typically micro SD cards
  - <u>Cellular transmission</u>: Is there sufficient cellular signal or WiFi? Where is the data transmitted? How is it transmitted? Do I need to buy a dedicated cellular plan?
  - <u>Computer connection</u>: Cords to connect sensor to computer (if required)
- ***What computer and software do I need?***
  - <u>Sensor-specific software</u>: Provided by sensor manufacturer
  - <u>Other software</u>: For data analysis (e.g., Excel), data download and transmission (e.g., PuTTY)
  - <u>Computer</u>: Must be sufficient to support all hardware and software

Before you start, read the user guide or instructions provided with your sensor. It's a good idea to test everything <u>before</u> you do your field evaluation to better understand your sensor and identify any potential problems.

Step 2: Making the Measurements

Do I need anything else?

- Yes! An important component of any field study or measurement project is a ***project notebook***.
- It should be a bound notebook, and weather-proof if used outdoors for field measurements.
- Mark out errors by drawing a single line through the error, and initial the change.
- Use the project notebook to document your activities in the field, and well as before and after field deployment.
- **Here are some examples of things to write in the *project notebook*:**
  - Tests and observations before the field evaluation
  - Details of field site visits – time, date, and duration; your activities and observations; status of sensors; nearby activities and unusual weather that may influence the measurements; problems observed and solutions
  - Interesting observations and decisions about data after deployment during data analysis.

Step 1: Planning a Sensor Evaluation

I've selected my sensor. Now what?

- One option is to contact your local air quality/natural resource board or agency. A good place to start is the Association of Air Pollution Control Agencies or the National Association for Clean Air Agencies.
- Reaching out to these agencies before starting a project can help you define your projects and goals, and direct you to the right contacts. They can also help you identify locations of reference monitoring sites, since they usually run them.
- Be aware that access to reference monitoring sites used for regulatory purposes will likely be restricted. You would have to gain permission from the local air quality agency to conduct research in close proximity to their secure monitoring locations.

The Air Quality System (AQS) contains ambient air pollution data collected by EPA, state, local, and tribal air pollution control agencies from over thousands of monitors. Here you can find instructions and links for obtaining AQS data.

Step 1: Planning a Sensor Evaluation

What other options do I have for collocating with a reference monitor?

- The reference (FRM/FEM) monitor used for collocation comparison does not need to be located at an official regulatory site.
- But it does need to be operated following approved quality assurance protocols. This can be done by any knowledgeable and reputable entity such as the following:
  - Federal, tribal, state, or local air quality/natural resources agency
  - University partner – typically with expertise in environmental engineering, atmospheric sciences, and similar fields – your local agency may be able to recommend university contacts
  - Air quality contractor

To help prepare for these initial conversations, it is recommended to review the questions listed in Appendix A of the Air Sensor Guidebook.

Step 1: Planning a Sensor Evaluation

How do I plan to collect data for scientific evaluation?

- Write up a plan (called a Quality Assurance Project Plan) that answers these questions:
  - What question are you trying to answer?
  - What data are needed?
  - Who will use the data and how will it be used?
  - Are there specific requirements for the data? Time of day? Season? Measurement duration?
  - How will data quality be evaluated?
  - Collocation with reference data!
  - Who will do the work?
    - List participants and their responsibilities in the project.
    - Include participants who can solve technical problems and understand data.

Click here to go back to the Approach steps slide.

View this video to learn more:

Quality Assurance Training Video

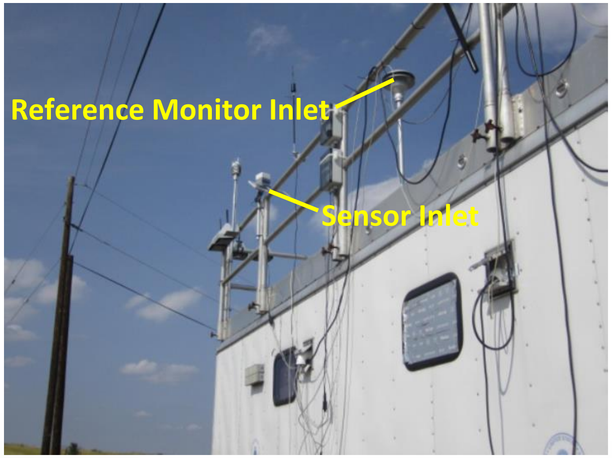
Download a template for your plan:

Quality Assurance Project Plan for Citizen Science Projects

Step 2: Making the Measurements

Where should I set up my sensors?

- Ideally, sensors and reference monitors should be within 10 meters (30 feet) of each other, and the inlets (where air enters the sensor/monitor) should be at about the same height.
- The movement of air around the sensor should not be blocked or hindered by any other structure or device.
- They should be protected from the weather.



Example of sensor inlet located near reference monitor inlet.

Example of a custom-made weather shelter for sensor evaluation.

Step 2: Making the Measurements

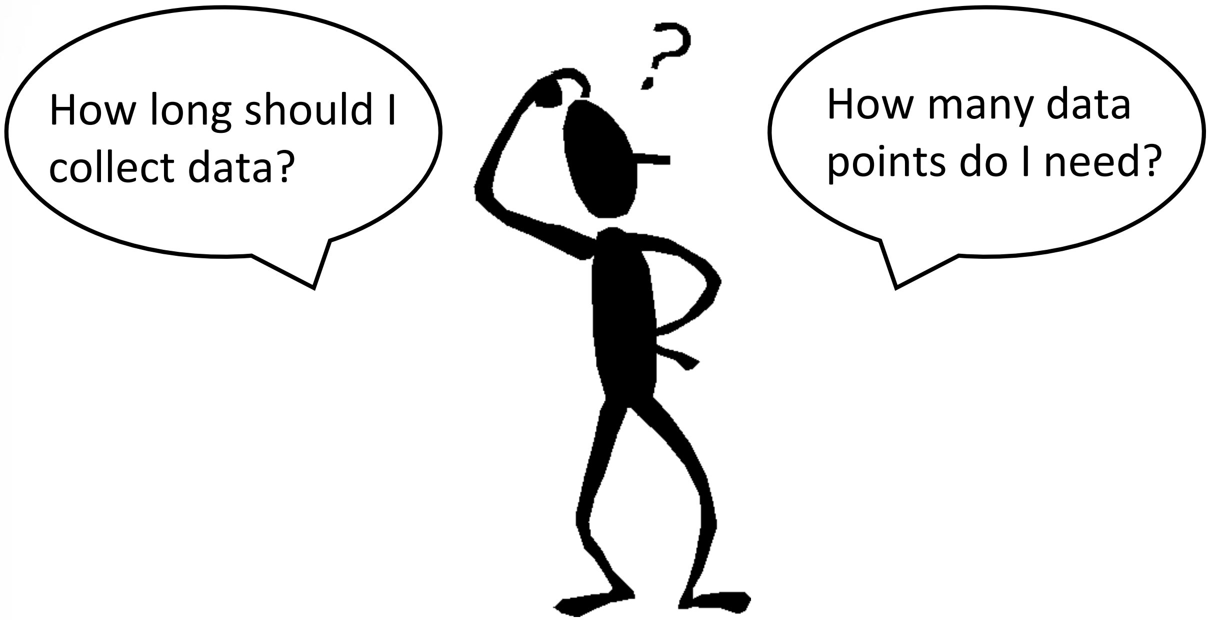
How do I make a useful comparison of the sensor and reference data?

- Find out how frequently the reference monitor reports data. Is it every 5 minutes? Every hour? Every 24 hours (typical of filter-based measurements)?
- Can your sensor report data at least as frequently, and at the same times, as the reference monitor? If possible, choose a sensor data reporting frequency somewhat shorter than the reference monitor data reporting frequency.

Here's an example of how to match sensor and reference data measurement periods:

1. ***Situation:*** **The reference monitor reports data every 5 minutes. The sensor data frequency choices are every 5 minutes, 1 minute, or 1 second.**
2. ***Choose sensor data frequency:*** **Choose 1 minute. (Choosing 1 second creates more data points than I need.)**
3. ***Average sensor data:*** **Take every five 1-minute sensor data points and average them to get a 5-minute data point to match the reference monitor's data reporting times.**

Step 2: Making the Measurements



Here are some suggestions for data collected for different time intervals:

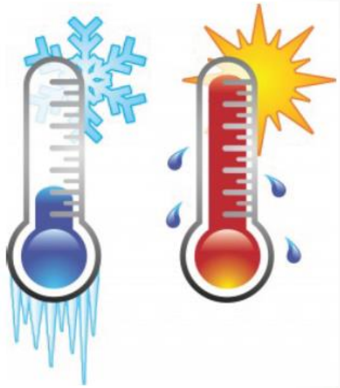
- 24-hour data – 1 month of successful data collection - ~30 valid data pairs
- 1-hour data – 2 weeks of successful data collection - ~500+ valid data pairs
- 5 min data – 1 week of successful data collection - ~2000+ valid data pairs

Step 2: Making the Measurements

Other factors to consider:

- Many pollutants follow seasonal patterns. If possible, do collocation measurements when the pollutant of interest is more likely to be at higher concentrations and more likely to be changing throughout the measurement period.

- Extreme temperature and relative humidity can affect sensor readings.



- Some pollutants or conditions may interfere with the pollutant you are trying to measure. Refer to the specifications provided by your sensor manufacturer for more information.

- Some sensors, like those for gases, may gradually lose their responsiveness over time and need to be replaced, typically after one year. This happens whether they are used or not. How can you tell? Their measurements will be trending downward when the reference measurements are not.

Step 2: Making the Measurements

Troubleshooting:

- Making measurements of any kind can have its challenges, especially in outdoor environments.
- Make sure you understand your sensor and what normal function looks like.
- Visit your monitoring site on a regular basis to catch problems and fix them before too many data points are lost.

- There are many things that can go wrong, and not all problems are due to a malfunctioning sensor. Here are a few common issues to check:
  - Is the sensor getting power? Check your power source or   reaker.
  - Has there been an unusual weather event?
  - Is there evidence of animals or insects interfering with the measurement?
  - Are all cable connections secure?
  - Is the inlet or outlet of the sensor blocked?
  - **NOTE ALL OBSERVATIONS IN YOUR PROJECT NOTEBOOK!**

Click here to go back to the Approach steps slide.

Step 3: Data Recovery and Review

Now that I have data, what should I do?

- Once you have data, it's important to review it to evaluate quality and identify problems.
- It's a good idea to review your data during the collection phase to identify problems that may affect your data and correct them, as well as at the end of your data collection to evaluate the whole data set.
- Things to look for when reviewing your data:
  - Abnormally high or low values (outliers)
  - Expected Patterns
  - Interferences
  - Drift or Shift

These features are defined, with examples, on the following slides. Use information and observations recorded in your field notebook to help you understand any problems you find in the data, and to help you decide how to handle them (e.g., exclude certain data points.)

Step 3: Data Recovery and Review

Outliers – data points that look out of place – much lower or higher than nearby data points

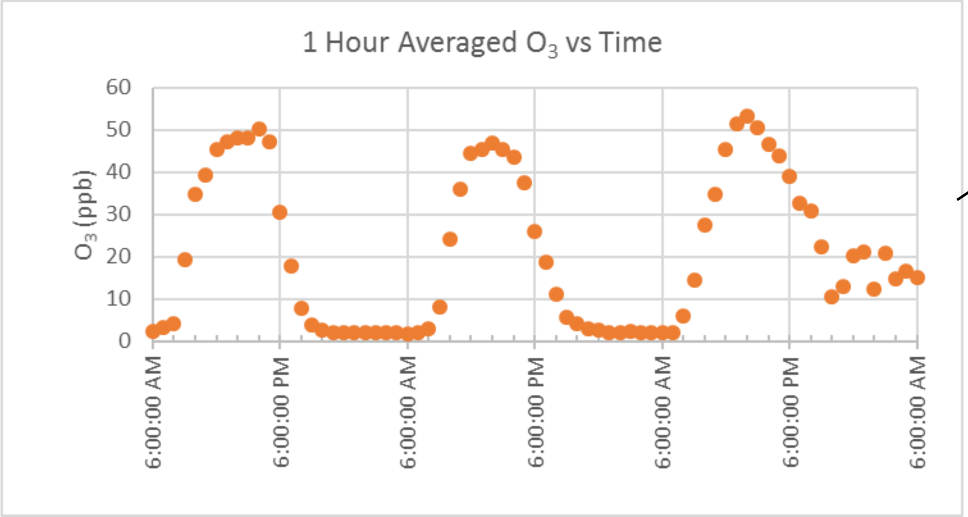
	A	B
1	Timestamp	PM 2.5 (ug/m^3)
2	12/7/2016 18:15	33.57
3	12/7/2016 18:20	35.91
4	12/7/2016 18:25	105.69
5	12/7/2016 18:30	110.24
6	12/7/2016 18:35	37.44
7	12/7/2016 18:40	38.16
8	12/7/2016 18:45	38.51
9	12/7/2016 18:50	39.18
10	12/7/2016 18:55	37.32
11	12/7/2016 19:00	38.16
12	12/7/2016 19:05	37.72
13	12/7/2016 19:10	38.14
14	12/7/2016 19:15	0.00
15	12/7/2016 19:20	37.55
16	12/7/2016 19:25	36.57

Field notes confirm I was visiting the sensor and left my car idling. That likely explains these high values.

This zero value is unusual. I wonder if this is a problem with the sensor or maybe data communication. I will keep an eye on the data to see if it happens again.

Step 3: Data Recovery and Review

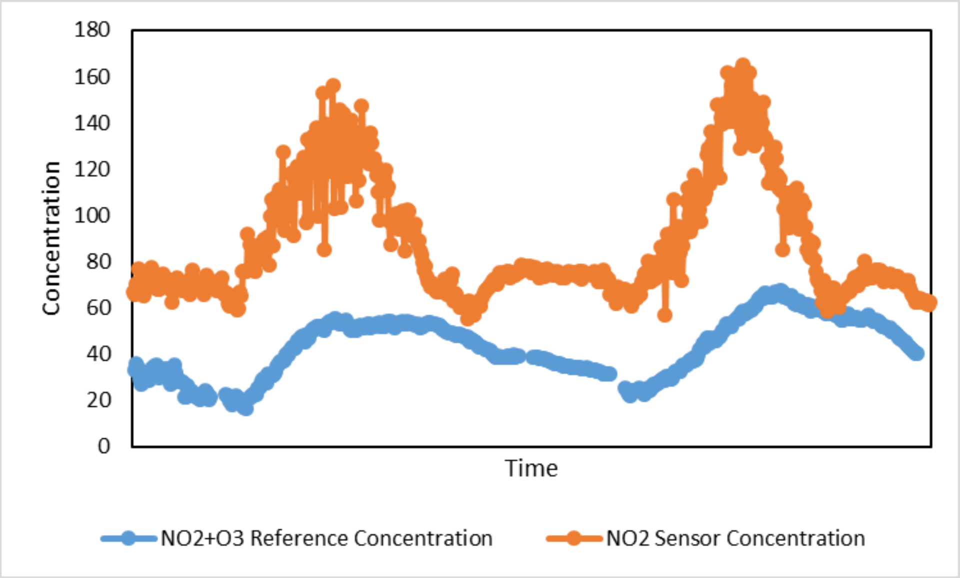
Expected Patterns – could be seasonal, day/night, or weekday/weekend patterns - absence of expected patterns may indicate a problem with your sensor or with your measurement approach



Ozone concentrations peak in late afternoon, as expected.

Step 3: Data Recovery and Review

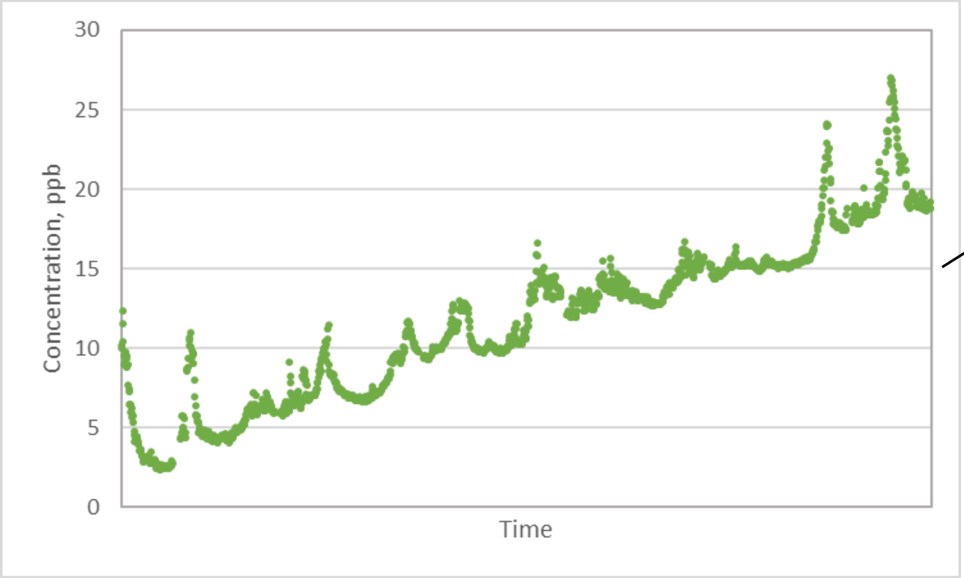
Interferences - may have a positive or negative effect on sensor response - can include pollutants or other chemical compounds that are not of interest, weather conditions, dirt/dust/insects.



The sensor is supposed to be measuring NO_2, but it's reporting concentrations higher than the combined reference NO_2 and O_3 concentrations. Could be a measurement interference.

Step 3: Data Recovery and Review

Drift or Shift - a gradual (drift) or sudden (shift) change in a sensor's response characteristics over time – can be positive or negative - may lead you to wrongly conclude that concentrations have increased or decreased over time



Concentrations reported by the sensor are increasing gradually over time. Looks like the sensors response is drifting.

Click here to go back to the Approach steps slide.

Step 4: Comparing the Data

Help! What do I do with all this data I have collected?

- Working with data sets and making comparisons may seem challenging, but there are tools available to make the job easier.

Wrestling with data? Take it to the MAT!

- The **MAT (Macro Analysis Tool)** is an Excel-based user-friendly macro tool developed by the EPA specifically for the purpose of comparing sensor data with reference data.
- Data sets don't have matching time-date stamps? Sensor data collected on a different time interval than the reference data? Periods of missing data? No problem – **MAT** takes care of that, and more!

Step 4: Comparing the Data

Do I have to use the MAT (macro analysis tool) to compare my data?

- No, you can use any software or data analysis tool to compare your data, based on your experience and comfort-level. But the **MAT** makes data comparison a lot easier!

Great! How do I use the MAT?

- The user inserts a column of sensor data onto the sensor page of the tool, and a corresponding column of reference data onto the reference page of the tool.
- Next, the user enters information in the control panel on the setup page, including the following:
  - Pollutant name
  - Start and stop dates and times
  - Reported units and sampling intervals
  - Desired averaging time interval
  - *Data completeness* criteria
- Then press RUN – the **MAT** takes care of the rest!

A complete list of features and instructions is available on the first page of the MAT. Click here to get a copy.

Step 4: Comparing the Data

Are data values missing or unusable?

- No data collection effort is perfect!
- Some expected data values may be missing due to downtime of the measurement device (e.g., power outages, maintenance).
- Some acquired data values may be unusable (e.g., nearby interfering activities, unusual conditions), or outliers (data value that is abnormally different from nearby data values). You may decide to exclude these from your calculations.
- Document your decisions about the data – what you did and why – in your project notebook.

The MAT will allow you to flag these unusable data points for exclusion from your analysis.

Step 4: Comparing the Data

What is Data Completeness?

<u>*Data completeness*</u> refers to the amount of usable data that was obtained, compared to the total amount expected. It is expressed as a percentage.

Click here to go back to the MAT overview slide.

<u>Example</u>:

- Suppose you want to take hourly data and average it to 24 hours.
- Now let's say that one of the 24-hour periods in your data had only 18 out of 24 hours of usable data.
- Now suppose that you decide you need each 24-hour period to be 90% complete. (Data completeness is another quantity that can be selected in the **MAT**.)
- In this example, there are not enough usable data points to meet this requirement, since the data is only 75% complete (18/24*100=75%), so an average would not be reported for that 24-hour period.
- ***The more data points available to average (higher data completeness percentage), the better that average represents the whole measurement period. Reporting the data completeness percentage applied to the data helps you and others understand your data better.***

Step 4: Comparing the Data

What information does the MAT produce?

Output page: Shows the two data sets being compared according to selections made in the control panel. Here's an example:

Date/time stamps for reference monitor and sensor have been matched.

Averaged Date Time	Reference Reference O3	Invalid Data Points	Sensor O3	Invalid Data Points
10/13/2016 12:00	47.53	0		18
10/13/2016 13:00	51.58	0	59.32	0
10/13/2016 14:00	54.93	0	59.67	0
10/13/2016 15:00	58.65	0	64.73	0
10/13/2016 16:00	54.33	0	60.55	0
10/13/2016 17:00	53.69	0	60.56	5
10/13/2016 18:00	43.13	0	48.78	0
10/13/2016 19:00	29.21	0	33.57	0
10/13/2016 20:00	11.68	0	14.17	0
10/13/2016 21:00	6.08	0	7.72	0
10/13/2016 22:00	7.42	0	8.12	0
10/13/2016 23:00	26.40	0	30.90	0

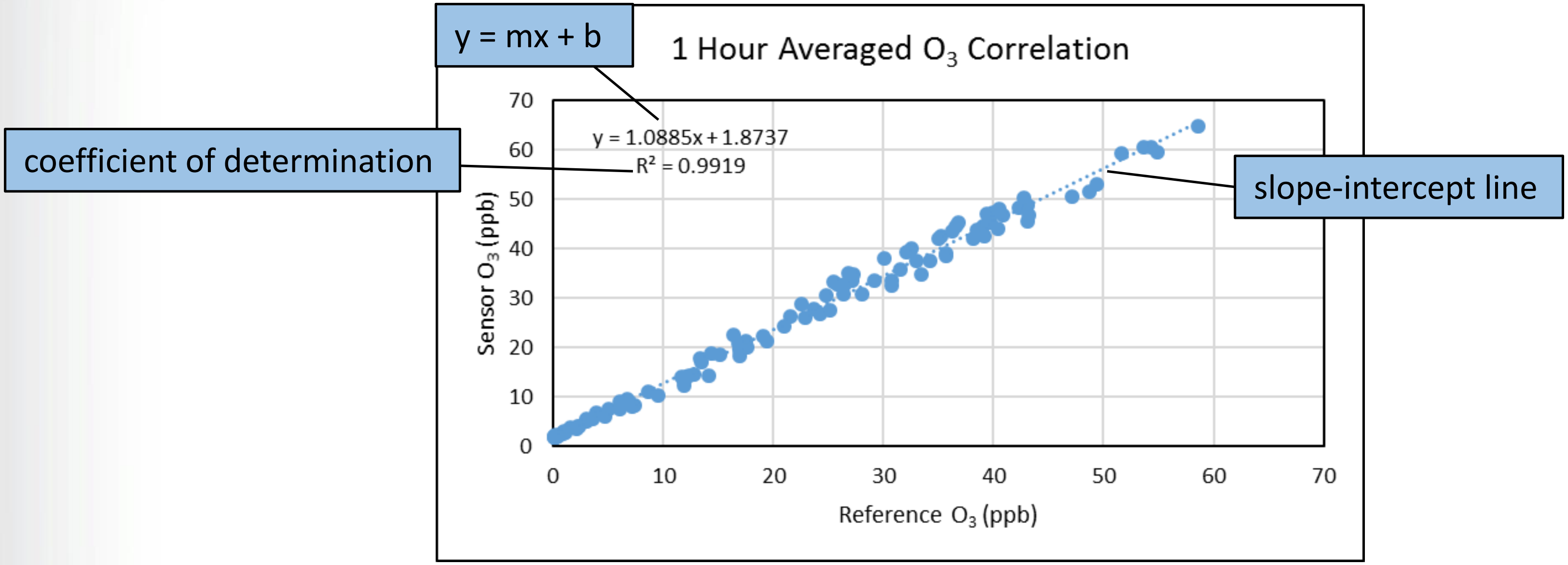
Here are the flagged or missing data points.

Graph page: Shows a time series comparison of the two data sets, a correlation comparison of the two data sets, plus some statistics.

This is information you typically need for your comparison no matter which software tool you choose for your data analysis. The following slides show examples and explain how to interpret the graphs and statistics.

Step 4: Comparing the Data

One way to compare the sensor data with the reference data is to plot the data in a <u>correlation graph</u>, as shown here:



The line going through the data is called the "slope-intercept" line and is represented by the equation <u>y = mx + b</u>. This equation is a statistical means of comparing the sensor data with the reference data. The <u>coefficient of determination</u>, represented by $\mathbf{R^2}$, is a measure of how close the data are to the slope-intercept line.

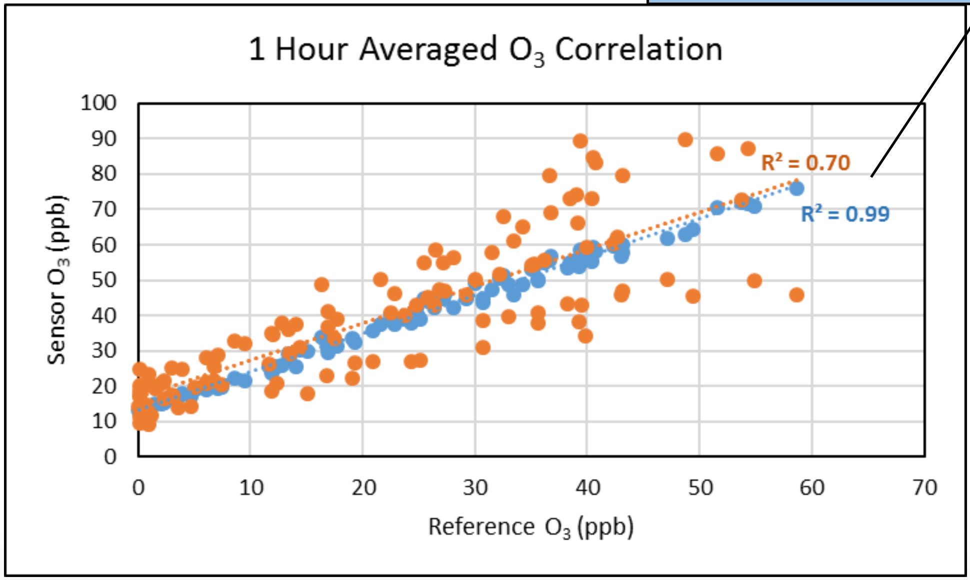
More information is provided on the following slides.
Here's a great instructional video on the topic: <u>y=mx+b video</u>

Step 4 : Comparing the Data

More about the coefficient of determination, R-squared

R-squared (R^2) is a statistical measure of how close the data are to the slope-intercept line - in other words, how much scatter is in the data. Its values range from 0 to 1. ***The closer R^2 is to 1, the stronger the agreement between the sensor and the reference data.***

R^2 = 0.99 shows more consistent agreement (less scatter) between sensor and reference than R^2 = 0.70

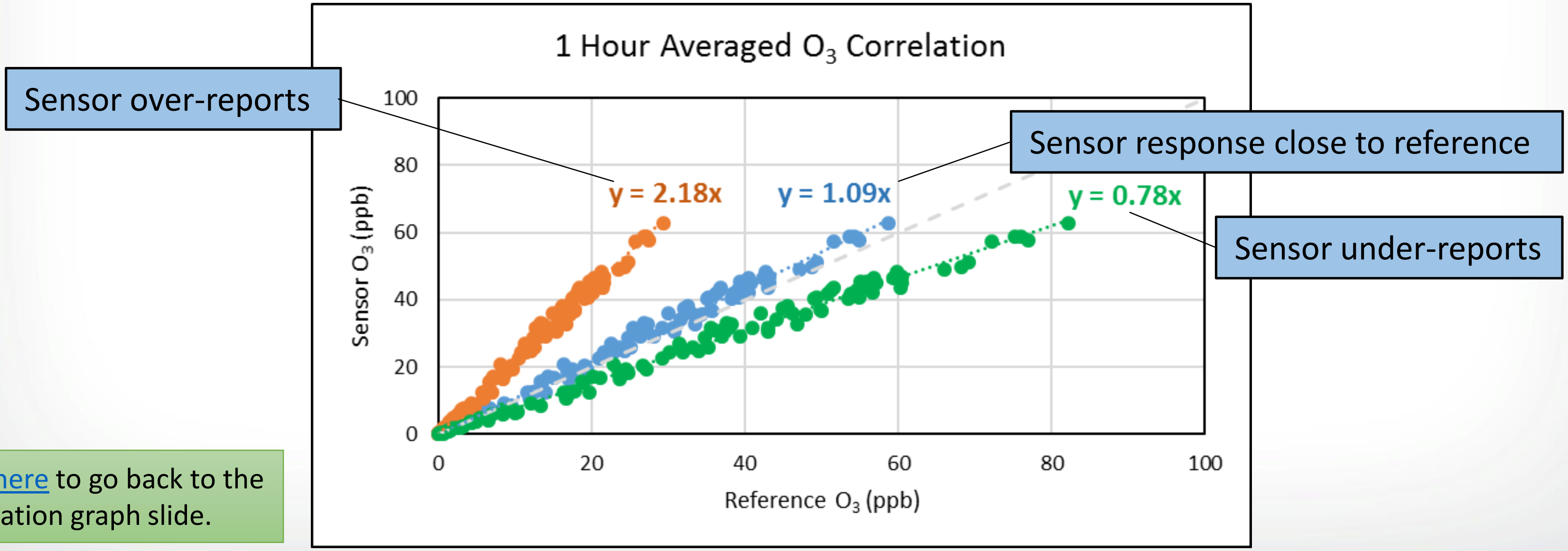


Click here to go back to the correlation graph slide.

Step 4 : Comparing the Data

More about the "slope-intercept" equation y = mx + b

- This equation represents the average behavior of the sensor data (vertical axis, represented by **y**) compared with the reference data (horizontal axis, represented by **x**).
- The **slope (m)** shows how similar, or different, the sensor measurements are compared with the reference measurements, on average. ***The farther "m" is from 1, the more the sensor over- or under-reports the concentration. The closer "m" is to 1, the more your sensor responds like (in proportion to) the reference monitor. The slope can be either a positive or negative value.***



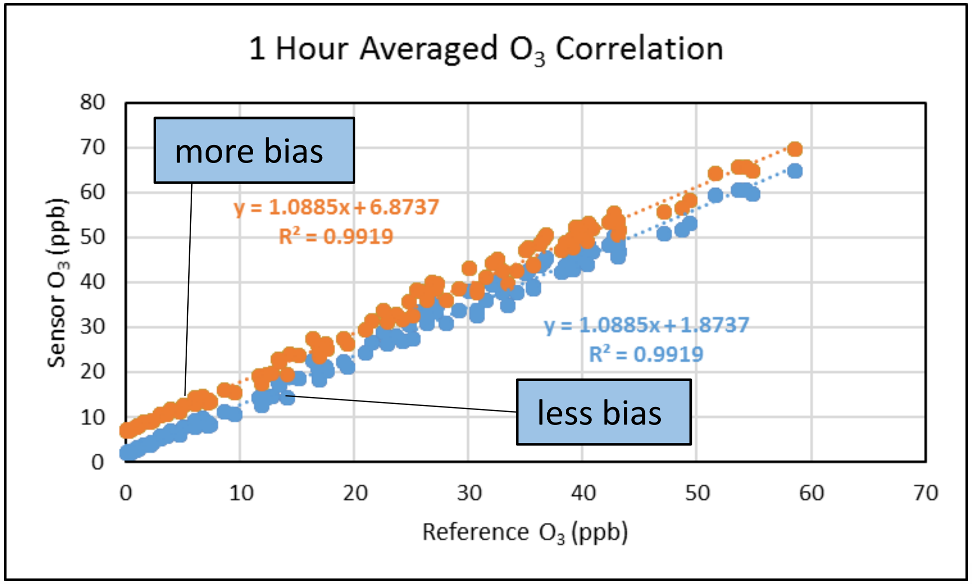
Click here to go back to the correlation graph slide.

Step 4 : Comparing the Data

More about the "slope-intercept" equation y = mx + b

The **intercept (b)** shows what the sensor measurement will be, on average, when the reference monitor is measuring zero concentration. ***The farther "b" is from zero, the more the sensor over- or under-reports a concentration. The closer "b" is to zero on the y-axis (vertical axis), the less the amount of "bias" in the sensor response.***

Click here to go back to the correlation graph slide.



Click here to go back to the Approach steps slide.

Step 5: Using Sensors

Suppose you want to take your sensors and do measurements away from a reference monitor. ***How can you still make sure your sensor data represent concentrations close to the true (reference) value?***

- Remember, the slope-intercept equation **y = mx + b** relates the sensor measurements to reference measurements:

$$\mathbf{sensor} = \mathbf{m} \cdot \mathbf{reference} + \mathbf{b}$$

- Use the values for **m (slope)** and **b (intercept)** you computed from the collocation data and apply these to the new sensor data so it is in better agreement with the reference data.

$$\mathbf{adjusted\ sensor\ concentration} = \frac{\mathbf{measured\ sensor\ concentration} - \mathbf{b}}{\mathbf{m}}$$

- Do this for ***each*** sensor you evaluate.
- Keep the $\mathbf{R^2}$ value in mind. The more scatter in the data (the farther R^2 is from 1), the less useful this adjustment will be.

Step 5: Using Sensors

Here are some examples of how to adjust sensor data to be closer to reference data

Example #1: Take a simple example where the **b** is zero, and **m** is 1.1.

- The equation becomes **SENSOR = 1.1*REFERENCE**.
- To make the new sensor values closer to what reference values would be, you have to *divide* the measured sensor value by the **slope** 1.1.

Example #2: Now let's make it more interesting. Suppose that **b** is equal to 1. That means the sensor measures 1 unit higher than the reference.

- The equation then becomes **SENSOR = 1.1*REFERENCE + 1**.
- To do the right adjustment, first subtract **b** (=1 in this example), *then* divide by **m** (=1.1 in this example).

In summary, the equation becomes

$$\textbf{Adjusted SENSOR concentration} = \frac{\textbf{Measured sensor concentration} - \mathbf{b}}{\mathbf{m}}$$

Step 5: Using Sensors

Now that I've done my collocation data comparisons, how do I decide if my sensors produce data that is good enough for my purposes?

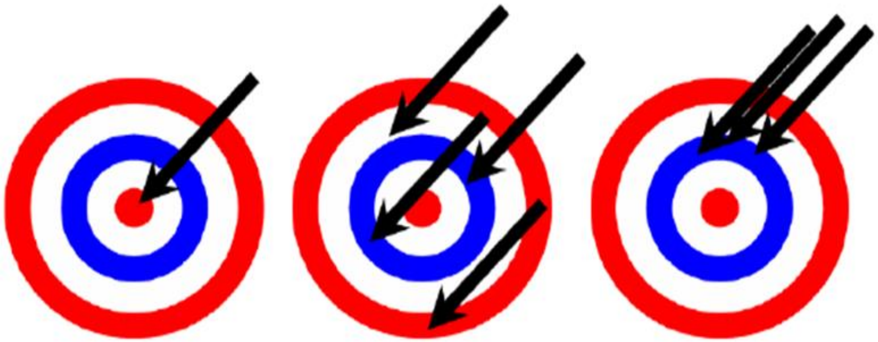
- Depends on the purpose!
- Collocation results provide an understanding about key performance characteristics of your sensor
- Go to the Air Sensor Guidebook to learn more. Chapter 4 provides information on how to collect useful data. Chapter 5 describes different types of sensor applications and performance goals for each.

Click here to go back to the Approach steps slide.

Additional Data Quality Information

Accuracy, Bias, and Precision – Important data quality parameters

- *Accuracy* is how close a measured value is to the actual (true) value.
- *Bias* is a systematic (built-in) error which makes all measurements wrong by a certain amount.
- *Precision* is how close the measured values are to each other.
- **These are illustrated in the following diagram:**



Accuracy= how close to "true" concentration

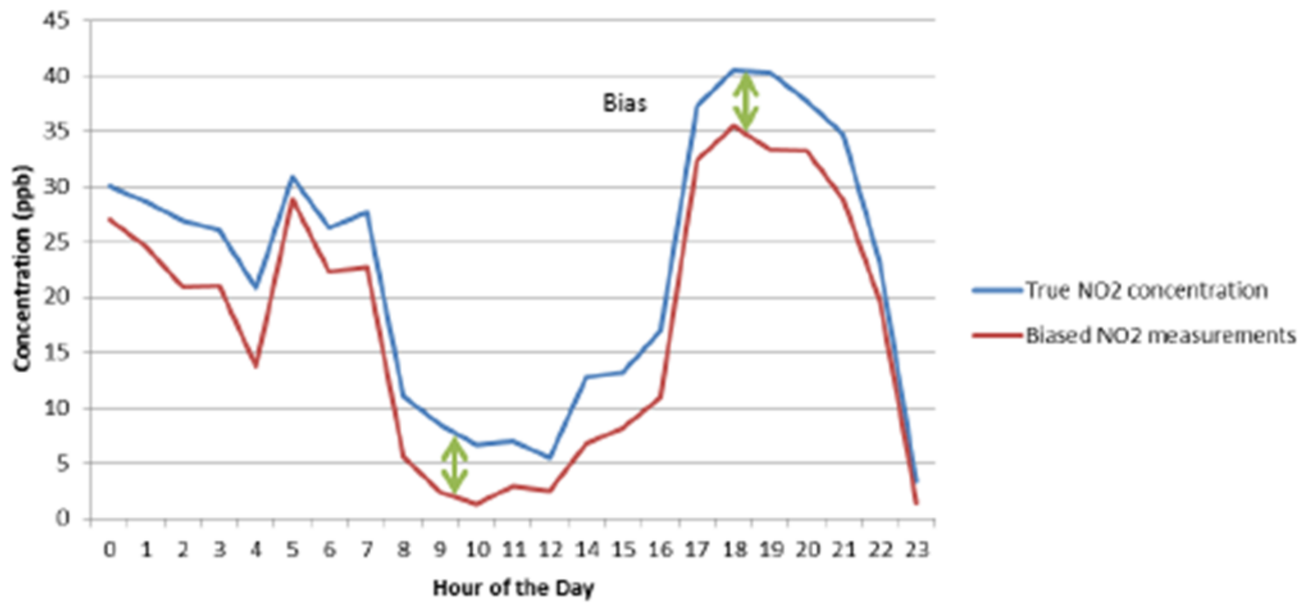
Precision= being able to consistently predict the same concentration

Bias= a systematic (common) error of reporting a value higher or lower than the true value

More information is provided on the following slides.
Here's a link to some great instructional videos: Bias and Precision Videos

More about bias

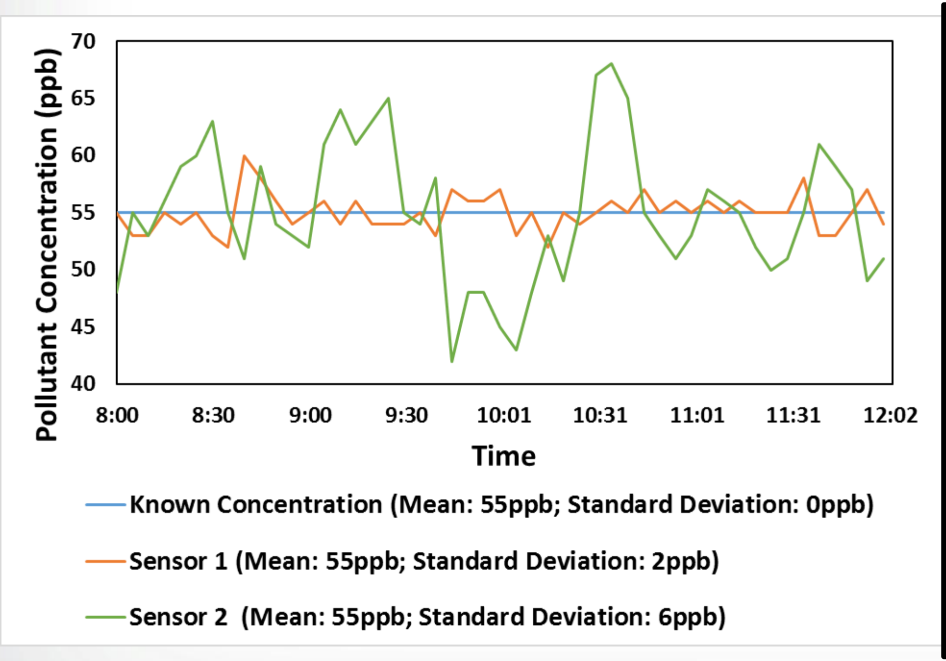
Bias is a persistent error in a measurement process that causes all measured values to be too high or too low by a certain amount, compared to the true (reference) value. This is the *intercept* value in the slope-intercept equation y = mx + b.



Comparison of a true value of NO2 and biased measurements of NO2.

More about precision

Precision is a measure of how close repeated measurements are to each other. It could be the same device making repeated measurements under the same conditions, or several of the same type of device making measurements at the same place and time.



What is standard deviation?

Standard deviation is a statistical measure of precision to describe how spread out numbers are. It is calculated by taking the square root of the *variance*.

And what is variance?

Variance is the average of the squared differences from the mean. *Mean* is just another word for average.

Additional Data Quality Information

How do I calculate variance and standard deviation?

There are many online resources that explain how to calculate variance and standard deviation. Here's one example: Variance and Standard Deviation

Here's a summary:

1. Calculate the average of the measurements. That's the mean.
2. Calculate the difference between the mean from step 1 and each individual measurement.
3. Square each of those numbers from step 2. That just means multiply each number by itself.
4. Add all those squared values from step 3 and divide by *one less* than the number of values. That means if there are "N" measurements, you divide by "N-1". Now you have the *sample variance*. (Your data set is just a *sample* of what could be measured.)
5. Calculate the square root of the *sample variance* from step 1. Now you have the *sample standard deviation.*

Software programs like Excel that can do these calculations, so you don't have to do all these steps by hand!

Conclusion

We hope you found this presentation useful in planning for your evaluation of low-cost sensors by collocating them with reference monitors. More information on sensor evaluation and applications can be found on the [Air Sensor Toolbox web page](). Good Luck!

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