Approaches to Air Sensor Calibration
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Motivation
- Tens of thousands of air sensors are deployed across the world, but to provide useful data, data producers must be able to ensure that the measurements are indicative of actual air pollution levels.
- There is no agreed-upon way to evaluate sensor networks (nor metrics to use), so it is difficult to compare disparate networks.
- A network’s data quality objectives (DQOs) must be well defined, so that validation criteria and methodologies can be developed to assess performance.

Air Sensor Network Reconciliation
To reconcile disparate sensor networks, sensor measurements need to be adjusted to compensate for local conditions, calibrated to ensure measurement accuracy, and routinely validated to provide confidence in reported air characteristics.

Calibration: Collocation of an air sensor with a reference at a reference site. Results are used to assess DQOs and to develop adjustment factors (slope, intercept, etc.).

Validation: A short-term check of sensor output, typically in situ.

Adjustment: Modification of raw sensor air measurements. This could be based upon adjustment factors determined during a collocation or dynamic factors determined by testing (i.e., sensor response under varying humidity conditions). Adjustments can vary in complexity from linear bias correction to complex machine learning.

Types of Reconciliation

<table>
<thead>
<tr>
<th>Method</th>
<th>Collocation (Permanent)</th>
<th>Collocation (Routine)</th>
<th>Collocation (Mobile)</th>
<th>“Golden Sensor”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Collocate one or more sensors at a reference site to characterize parameters such as drift, sensor aging, cross-interferences, and seasonal changes in performance.</td>
<td>Routinely, at regular intervals, collocate a sensor at a reference site to assess performance.</td>
<td>Use a mobile lab tocollocate and assess performance in situ using FEM/FRM instruments.</td>
<td>Use a sensor that has been validated through collocation with a reference to assess another sensor’s performance in situ.</td>
</tr>
<tr>
<td>Relative Cost</td>
<td>Low</td>
<td>Moderate</td>
<td>High (labor intensive)</td>
<td>Moderate-high (labor)</td>
</tr>
<tr>
<td>Sensor-to-Sensor Comparison</td>
<td>Allows</td>
<td>Allows</td>
<td>None</td>
<td>Sometimes</td>
</tr>
<tr>
<td>Identity Location Bias</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Some</td>
</tr>
<tr>
<td>Identity Failed Sensors</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Comments</td>
<td>Relatively short collocation period.</td>
<td></td>
<td></td>
<td>Could be facilitated with higher-end air sensors; potential for propagation of errors; calibration is not linear.</td>
</tr>
</tbody>
</table>

Air Sensor Adjustment & Machine Learning
Possible uses:
- Adjusting raw sensor readings.
- “Hopping” calibrations from one site to another.
- Identifying outliers.

International Examples of Air Sensor Reconciliation
- China (SailHero)
  To validate 10,000s of sensors, developed a comprehensive system of initial calibration, machine learning algorithms for “calibration jumping” and outlier identification, and in situ calibration using a mobile system outfitted with FEM instruments.
- India (Shakti Foundation with STI Guidance)
  Hundreds of sensors being deployed with initial and routine collocation tests with a reference.
- Accra, Ghana (EPA Ghana/U.S. EPA/STI)
  Twenty-three PM sensors were collocated before deployment (no FEM available) and will be routinely collocated with a FEM. Four sites have three sensors permanently collocated with an FRM.
- Sacramento, CA (SCAQMD/STI)
  Wintertime air toxics study used an initial and final collocation, permanent collocation of several sensors, and machine learning techniques to reconcile the network.
- Southern California (SCAQMD)
  SCAQMD is performing long-term and routine collocation of hundreds of sensors and is exploring network-wide adjustments with Aeroulso using AirNow data.

Proposed Frameworks for Air Sensor Reconciliation
Reconciliation approaches can be leveraged separately or in combination to support air sensor network validation.

Small Operational Networks
Small networks need to leverage FEM/FRM sites for routine validation of sensor performance. Air districts will be able to answer questions and provide insights.

Collocation (Routine): Allows for robust adjustment algorithms to be generated and helps identify failed sensors.

Large Operational Networks
Large networks require a hybrid approach, incorporating different reconciliation types and tools.

Collocation (Permanent): Provides crucial information on sensor aging, seasonal biases, etc.

Conclusions
- Multiple calibration techniques are in use today, providing a range of advantages and disadvantages with respect to cost, robustness, and types of errors identified.
- Multiple validation approaches used together can support robust air sensor networks.
- Reference/regulated sites are still crucial, especially at the community level, so users can validate their measurements.
- Air sensor data adjustment with algorithms and machine learning will play a role, but that role is still being defined.

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