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.

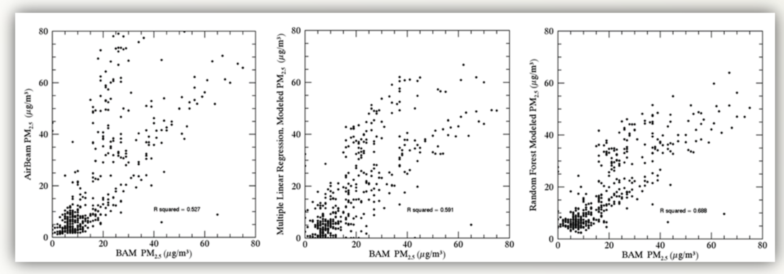
Types of Reconciliation

Method	Collocation (Permanent)	Collocation (Routine)	Collocation (Mobile)	"Golden Sensor"
Description	Collocate one or more sensors at a reference site to characterize parameters such as drift, sensor aging, cross-interferences, and seasonal changes in performance.	Routinely, at regular intervals, collocate a sensor at a reference site to reassess performance.	Use a mobile lab to routinely assess performance *in situ* using FRM/FEM instruments.	Use a sensor that has been validated through collocation with a reference to assess another sensor's performance *in situ*.
Relative Cost	Low	Moderate	High (labor intensive)	Moderate-high (labor)
Sensor-to-Sensor Comparison	Allows	Allows	None	Sometimes
Identify Location Bias	No	No	Yes	Some
Identify Failed Sensors	No	Yes	Yes	Yes
Comments			Relatively short collocation period.	Could be facilitated with higher-end air sensors; potential for propagation of error; calibration is now four degrees from original standard.

Air Sensor Adjustment & Machine Learning

Possible uses:

- Adjusting raw sensor readings
- "Hopping" calibrations from one site to another
- Identifying outliers



ML methods show improvement in sensor accuracy over traditional methods. Left: Linear Regression (R^2=0.527), Center: Multiple Linear Regression (R^2=0.591), Right: Random Forest Model (R^2=0.688).

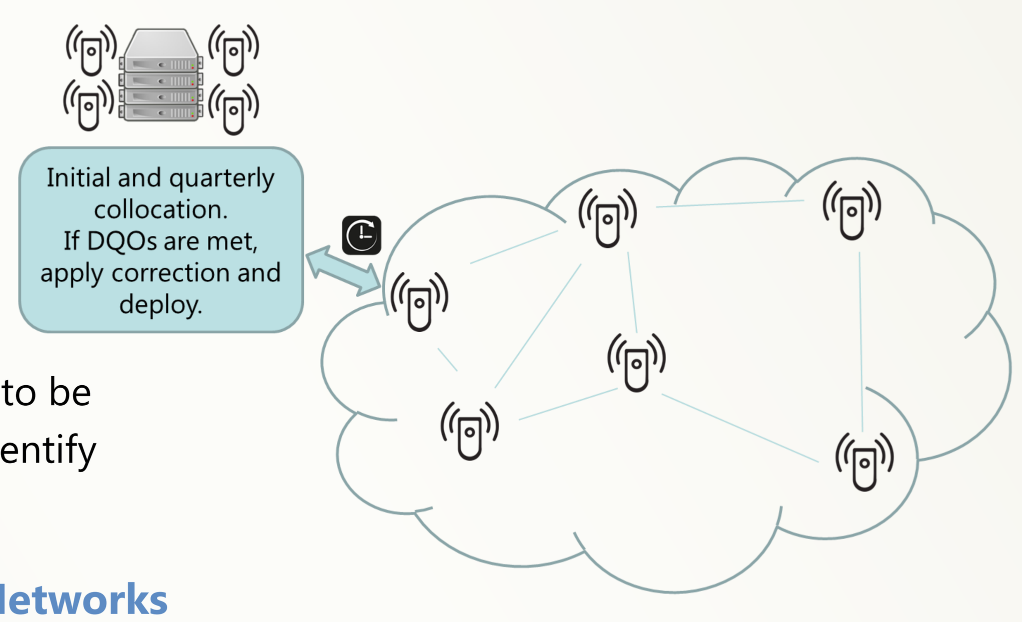
Proposed Frameworks for Air Sensor Reconciliation

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.



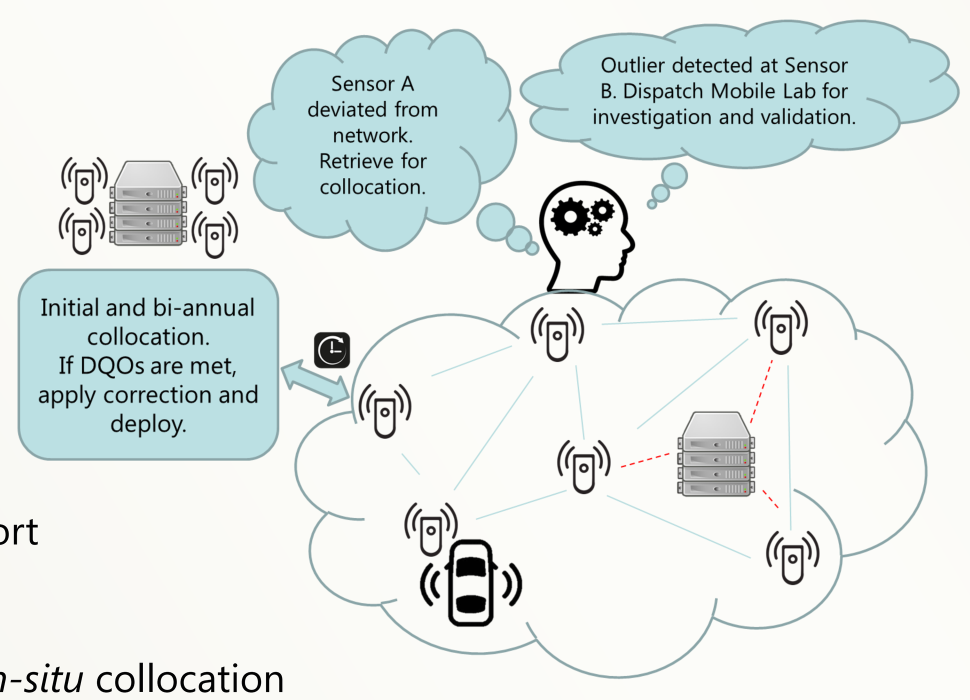
Large Operational Networks

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

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

Collocation (Routine): Allows for more robust adjustment algorithms to be generated.

Collocation (Mobile): Validates sensor-identified hotspots and provides short collocation periods.



Golden Sensor: Enables *in-situ* collocation for longer periods than a mobile platform.

Machine Learning and AI: Assists network operators in identifying short-term deviations (that may be caused by a release of pollution that requires investigation) and long-term deviations (that may be caused by sensor fouling).

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 (SMAQMD/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 Aeroqual using AirNow data.

Community Monitoring and Citizen Science

Community monitoring and citizen science using air sensors present unique challenges for data quality. Considerations include:

- Encourage use of tested sensors
- Educate on limitations of sensors
- Establish centrally located validation stations at parks or other community centers
- In California, this could be based around monitoring sites established by CA AB 617, BAAQMD Rule 12-15, or SCAQMD Rule 1180

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/regulatory sites are still crucial, even 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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