Low-Cost Sensors:
The “How” of Performance Evaluation, Network Design, and Data Handling

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Brandon Feenstra, Air Quality Specialist

St. Louis, MI – September 2, 2018
Outline

• Background
• Air Quality Sensor Performance Evaluation Center (AQ-SPEC)
• Field Testing
• Laboratory Testing
• Network Design & Data Management Platforms

Disclaimer
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Air Quality Sensing

- Rapidly proliferating
- Tremendous potential
  - Low-cost?
  - Ease of use
- Multiple potential applications
  - Spatial/Temporal air quality info
  - Fence-line applications
  - Community monitoring
- Need to systematically evaluate their performance
  - Accuracy, precision, durability and overall reliability
  - Calibration and drift
  - Other performance issues

...and more!
Air Quality Sensing – Low-Cost/Consumer-grade?

- Raw sensor, raw sensing head
  - $15 to $400

- Sensing unit: ≥1 raw sensing head + housing + user interface + external communication + power capabilities
  - $150 to $400 to $7,000
Established in July 2014
Over $600,000 initial investment (funded by AQMD Board)

Main Goals & Objectives
- Provide guidance & clarity
- Promote successful evolution and use of sensor technology
- Minimize confusion

Sensor Selection Criteria
- Commercially available
- Criteria pollutants & air toxics
- Real- or near-real time, time resolution ≤ 5-min
- High sensitivity at ambient level and low concentrations
- Continuous operation for two months, using AC/DC power
- Retrievable data
- Low-cost...?
How do sensors reach AQ-SPEC for an evaluation:

- Internet search by AQ-SPEC team
- Contacted by:
  - Manufacturers
  - Vendors
  - Developers
  - Integrators
  - Citizen Scientists
  - Air Quality Experts/Researchers
  - Other AQMD/APCD Agencies

2014 – 2018: Over 30 PM sensors evaluated
Field Testing

- Sensor tested in triplicates
- Two month deployment (various time intervals, random)
- Location:
  - SCAQMD Riverside-Rubidoux Air Monitoring Station
  - Inland site
  - Fully instrumented
- Land use: Apartment complexes, single-family residences, school grounds, retail outlets, vacant lots
- Potential PM sources:
  - California State Route 60 (1 km away)
  - Small private airport (1.5 km away)
Prior to an evaluation, a bench test in the SCAQMD Lab is performed:

- Review sensor documentation including manual, operating procedures
- Evaluate power options: cable, battery, solar
- Evaluate data acquisition options: local storage, laptop data logging, cloud-based
- Evaluate raw data output format
- Evaluate functionality of On/Off switch
### PM Sensors

<table>
<thead>
<tr>
<th>Sensor Image</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Pollutant(s)</th>
<th>Approx. Cost (USD)</th>
<th>&quot;Field R²&quot;</th>
<th>&quot;Lab R²&quot;</th>
<th>Summary Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aer sensual (AQI v.0.5)</td>
<td>Optical</td>
<td>PM₁₀₀</td>
<td>~$3,000 (multi-sensor)</td>
<td>R² = 0.84 to 0.87</td>
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<tr>
<td>Air Quality Egg (version 1)</td>
<td>Optical</td>
<td>PM₁₀₀</td>
<td>~$125</td>
<td>R² = 0.79 to 0.94</td>
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<tr>
<td>Air Quality Egg (version 2)</td>
<td>Optical</td>
<td>PM₁₀₀</td>
<td>~$250</td>
<td>R² = 0.80</td>
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<tr>
<td>Alphameter (OPC-92)</td>
<td>Optical</td>
<td>PM₁₀₀, PM₁₀, PM₀₅</td>
<td>~$145</td>
<td>R² = 0.63 to 0.80, R² = 0.38 to 0.60, R² = 0.41 to 0.50</td>
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<tr>
<td>Cal</td>
<td>Optical</td>
<td>PM₁₀₀, PM₁₀₀, PM₁₀₀, PM₀₅</td>
<td>~$300</td>
<td>R² = 0.82 to 0.91, R² = 0.80 to 0.85</td>
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<tr>
<td>Clariti (Nest)</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$1,500</td>
<td>R² = 0.73 to 0.76</td>
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<tr>
<td>Dylos (DC1100)</td>
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<td>PM₀₅, PM₁₀₀</td>
<td>~$1,200</td>
<td>R² = 0.91 to 0.95, R² = 0.80 to 0.89</td>
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<tr>
<td>Fenvair</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$120</td>
<td>R² = 0.89</td>
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<td></td>
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<tr>
<td>HabitatAir (Airomer)</td>
<td>Optical</td>
<td>PM₀₅, PM₁₀₀</td>
<td>~$1,200</td>
<td>R² = 0.86 to 0.90, R² = 0.87, R² = 0.87</td>
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<tr>
<td>Nanosense (NanoN II)</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$200</td>
<td>R² = 0.32 to 0.75</td>
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<tr>
<td>EQAir (4th Avenue)</td>
<td>Optical</td>
<td>PM₀₅, PM₁₀₀</td>
<td>~$370</td>
<td>R² = 0.69 to 0.71, R² = 0.32 to 0.40, R² = 0.24 to 0.41</td>
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<tr>
<td>Met One (E-Sampler)</td>
<td>Optical</td>
<td>PM₀₅, PM₁₀₀, PM₁₀₀, PM₀₅, PM₁₀₀, TSP</td>
<td>~$1,500</td>
<td>R² = 0.52 to 0.62</td>
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<tr>
<td>Met One (Neighborhood Monitor)</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$1,500</td>
<td>R² = 0.52 to 0.62</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

### PM Sensors

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<tr>
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<th>Summary Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo (China) (Sens)</td>
<td>Optical</td>
<td>PM₁₀₀</td>
<td>~$150</td>
<td>R² = 0.91 to 0.95, R² = 0.97 to 0.99</td>
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<td>Nanosense (Parthenon)</td>
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<td>Origlas (Laser Egg)</td>
<td>Optical</td>
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<td>~$200</td>
<td>R² = 0.58 to 0.93</td>
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<td></td>
<td></td>
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<tr>
<td>Perkin Elmer (LID)</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$5,000</td>
<td>R² = 0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PurpleAir (PA-1)</td>
<td>Optical</td>
<td>PM₀₅, PM₁₀₀</td>
<td>~$150</td>
<td>R² = 0.91 to 0.95, R² = 0.90 to 0.94, R² = 0.77 to 0.92, R² = 0.32 to 0.44, R² = 0.95</td>
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<tr>
<td>PurpleAir (PA-1 Indoor)</td>
<td>Optical</td>
<td>PM₀₅, PM₁₀₀</td>
<td>~$110</td>
<td>R² = 0.75 to 0.94, R² = 0.16 to 0.46</td>
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<td>PurpleAir (PA-2)</td>
<td>Optical</td>
<td>PM₀₅, PM₁₀₀, PM₁₀₀</td>
<td>~$200</td>
<td>R² = 0.95 to 0.99, R² = 0.93 to 0.83, R² = 0.66 to 0.70, R² = 0.84 to 0.95</td>
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<tr>
<td>RTI (Membran)</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$2,000</td>
<td>R² = 0.65 to 0.90</td>
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<tr>
<td>Saltsmart (Pore Monitoring)</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$700</td>
<td>R² = 0.73</td>
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<tr>
<td>Shimpo (PM Evaluation KPO)</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$1,000</td>
<td>R² = 0.80 to 0.90</td>
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<tr>
<td>Spack</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$300</td>
<td>R² = 0.32</td>
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<td></td>
<td></td>
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<tr>
<td>TSG (Air Acorn)</td>
<td>Optical</td>
<td>PMfono, PM₁₀₀, PM₁₀₀, PM₁₀₀, PM₁₀₀, PM₁₀₀, PM₁₀₀, PM₁₀₀</td>
<td>~$1,500</td>
<td>R² = 0.65 to 0.80, R² = 0.80 to 0.90, R² = 0.93 to 0.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eMoo</td>
<td>Optical</td>
<td>PM₀₅</td>
<td>~$300</td>
<td>R² = 0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Results

www.aqmd.gov/aq-spec/evaluations/summary

Previous Chamber Work

Spinelle et al., 2013
Institute for Environment and Sustainability
Joint Research Centre, European Commission

Williams et al., 2014
Office of Research and Development National
U.S. Environmental Protection Agency

Wang et al., 2015, Aerosol Sci Tech

Austin et al., 2015, PLOS One
University of Washington
- **Particulates** on integrated filter samples:
  - Mass by gravimetric analysis
  - PM components by IC, ICP-MS, XRF, TOM, GC-MS (levoglucosan)

- **Gas-VOC** by GC, GC-MS, HPLC, and UHPLC

- **Asbestos** by polarized light microscopy, X-Ray Diffraction

- **PM deposition** by microscopy, XRF, and SEM-EDS

- **Cr⁶⁺** by ICP-MS

- **TGA, pH** and **vapor pressure**

- **TCA, CO, CH₄, CO₂**

- **Compliance:**
  Paints, coatings, petroleum products, adhesives, lubricants and stack samples for VOC, inorganic components (e.g., metals, acids, SOx and NOx)
1. Chamber system (sophisticated HVAC)
2. “Zero air” generation system
3. Two Particle systems
4. FEM/FRM/BAT reference instruments
5. Integrated software
Outer chamber
- Made of stainless steel
- Shape: Rectangular
- Volume: 1.3 m$^3$
- HVAC system
- Louvered ceiling surface
- Set of two fans

Inner chamber
- Teflon-coated Stainless Steel
- Shape: Cylindrical
- Volume: 0.11 m$^3$
Ethernet & power ports

USB & power ports

WiFi

Bluetooth
Highly precise temperature control

Temperature range: -32 to +177 °C

Temperature was increased from 5 °C to 40 °C. Each step is 30 min.
More precise RH control at higher temp

At 20 °C, SD range: ± 0.8% to ±3.5%

At low temp and high RH, RH oscillates near set points, due to humidifying and dehumidifying cycle

Relative Humidity range: 5 to 95 %
2. “Zero air” generation system
“Zero-Air” system: Dry, gas- and particle-free dilution air system

- One heated catalyst scrubber for the removal of CO
- Two scrubbers of activated carbon for the removal of VOC and NO₂
- Two scrubbers of NaMNO₄ impregnated on porous alumina (Purafil) for the removal of H₂S, SO₂, NOₓ, and HCHO
- One cylinder of MnO₂/CuO catalyst for the removal of ozone O₃
- One cylinder of 13X molecular sieve
- Two cylinders of CaSO₄ to further dry the previously compressed and dried outside air
- One in-line HEPA filter for the removal of particulate impurities
3. Two Particle systems
4. FEM/FRM/BAT reference instruments
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Measures</th>
<th>Conc. Range</th>
<th>LDL</th>
<th>Measurement Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRIMM</td>
<td>EDM180</td>
<td>PM$<em>{10}$, PM$</em>{2.5}$, and PM$_{1}$</td>
<td>0.1-1,500 µg/m$^3$</td>
<td>0.1 µg/m$^3$</td>
<td>light scattering</td>
</tr>
<tr>
<td>TSI</td>
<td>3321</td>
<td>0.5 to 20 µm</td>
<td>0-10,000 particles/m$^3$</td>
<td>0.001 particle/m$^3$</td>
<td>double-crest optical</td>
</tr>
<tr>
<td>TSI</td>
<td>3091</td>
<td>5.6 to 560 nm</td>
<td>N/A</td>
<td>N/A</td>
<td>electrical mobility</td>
</tr>
<tr>
<td>Teledyne</td>
<td>M651</td>
<td>ultrafine particle conc, &gt; 7 nm</td>
<td>0.001 to $10^6$ particles/cm$^3$</td>
<td>N/A</td>
<td>Water-based CPC</td>
</tr>
</tbody>
</table>
Particle systems control software

Gas analyzers and chamber Temp/RH sensors control software
# T/RH combinations for sensor testing

<table>
<thead>
<tr>
<th>Relative Humidity (%)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 °C / 15% (Low / Low)</td>
<td>20 °C / 15%</td>
</tr>
<tr>
<td>5 °C / 40%</td>
<td>20 °C / 40%</td>
</tr>
<tr>
<td>5 °C / 65%</td>
<td>20 °C / 65%</td>
</tr>
</tbody>
</table>

### PM$_{2.5}$/PM$_{10}$ Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>PM$<em>{2.5}$/PM$</em>{10}$ (µg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>10</td>
</tr>
<tr>
<td>Low</td>
<td>15</td>
</tr>
<tr>
<td>Medium</td>
<td>50</td>
</tr>
<tr>
<td>High</td>
<td>150</td>
</tr>
<tr>
<td>Very High</td>
<td>300</td>
</tr>
</tbody>
</table>
Particle systems (i.e., PALAS and TOPAS)
  • Theory of operation
  • Factors in determining aerosol concentrations (i.e., recipes)
  • Aerosol atmospheres
    o Stability
    o Reproducibility
    o Decay experiment
  • Particle size distribution

Sensor evaluation experiments - Examples

Aerosol Generation System

Credit: Kyrstin Fornace
Factors in determining aerosol conc.:

- Salt type and concentration (e.g., 17% KCl in DI water)
- Pre-/Injection/post-/pause/no. of cycles
- Compressed air pressure
- Fans speed

A PALAS concentration ramping experiment

<table>
<thead>
<tr>
<th></th>
<th>pre-inj</th>
<th>inj</th>
<th>post-inj</th>
<th>off</th>
<th>cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>step 1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>32</td>
<td>4</td>
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<tr>
<td>step 2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>32</td>
<td>2</td>
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<tr>
<td>step 3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>32</td>
<td>0</td>
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<tr>
<td>step 4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>32</td>
<td>0</td>
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<tr>
<td>step 5</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>32</td>
<td>0</td>
</tr>
</tbody>
</table>
- Wide range of concentrations: 6 – 230 μg/m³
- Stability (5 different experiments, 300 min each)
- Reproducibility (3 repeated experiments, shaded area is std error)
• 100 µg/m³
• GRIMM EDM180
• 0.25-32 µm in aerodynamic particle diameters
• 31 in total size channels
- T = 0 min, started experiment, fans frequency at 20 Hz
- T = 150 min, adjusted to 40 Hz
- T = 210 min, adjusted to 60 Hz
Dust dispenser

Figure 4: Principle of the SAG 410/U
- ISO 12103-A4 (Coarse) Arizona Test Dust
- Dryness (Hygroscopicity) of the standard dust
  - Dust is vacuum dried prior to use
  - Dust box is purged with dry air continuously
- Feeding belt speed (%)
- Chamber fans speed

APS conc. is corrected for ATD density (2.6 g/cm³)

<table>
<thead>
<tr>
<th>Feed (s)</th>
<th>Cycle (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>step 1</td>
<td>1</td>
</tr>
<tr>
<td>step 2</td>
<td>1</td>
</tr>
<tr>
<td>step 3</td>
<td>2</td>
</tr>
<tr>
<td>step 4</td>
<td>4</td>
</tr>
<tr>
<td>step 5</td>
<td>6</td>
</tr>
</tbody>
</table>
Relative Humidity Ramping Experiments 15% to 40% to 65%

AQ-SPEC
Air Quality Sensor Performance Evaluation Center

5 °C

20 °C

35 °C

Low Conc.

Med Conc.

High Conc.
Feed: 5 s; Cycle: 20 s
Fan speed: 10 Hz
20 °C, 40% RH
Equilibrium PM$_{10}$ Concentration: 80 µg/m$^3$
• $T = 0$ min started experiment at 10Hz (Feed 5s; Cycle 20s), 80 $\mu g/m^3$
• $T = 120$ min, adjusted frequency at 20 Hz, 62 $\mu g/m^3$
• $T = 180$ min, adjusted frequency at 40 Hz, 41 $\mu g/m^3$
• $T = 240$ min, adjusted frequency at 60 Hz, 23 $\mu g/m^3$
### T/RH combinations for sensor testing

<table>
<thead>
<tr>
<th>Relative Humidity (%)</th>
<th>Temperature (°C)</th>
<th>Pollutant</th>
<th>PM Level/units (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Low / Low)</td>
<td>5 °C / 15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 °C / 15%</td>
<td>Very low</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>35 °C / 15%</td>
<td>Low</td>
<td>15</td>
</tr>
<tr>
<td>(High / High)</td>
<td>5 °C / 40%</td>
<td>Medium</td>
<td>50</td>
</tr>
<tr>
<td></td>
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<td>High</td>
<td>150</td>
</tr>
<tr>
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<td>Very High</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>5 °C / 65%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 °C / 65%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35 °C / 65%</td>
<td></td>
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</tr>
</tbody>
</table>
Evaluation Parameters:

- Intra-model variability
- Accuracy
- Precision
- Coefficient of Determination ($R^2$)
- Data Recovery
- Climate Susceptibility
- Interferents (e.g., monodisperse aerosols)
Intra-model variability (%) = \frac{\text{Mean}_{\text{highest}} - \text{Mean}_{\text{lowest}}}{\text{Mean}_{\text{average}}} \times 100

where,
\text{Mean}_{\text{highest}} \text{ is the highest of the three sensors' average concentrations}
\text{Mean}_{\text{lowest}} \text{ is the lowest of the three sensors' average concentrations}
\text{Mean}_{\text{average}} \text{ is the average of the three sensors' average concentrations}

Accuracy
\begin{align*}
A (\%) &= 100 - \frac{|\bar{X} - \bar{R}|}{\bar{R}} \times 100
\end{align*}

where,
\bar{X} \text{ is the average concentration measured by the three sensors throughout the steady-state period considered}
\bar{R} \text{ is the reference instrument average concentration during the same steady-state period}
Precision

\[ P(\%) = 100 - \frac{\text{SE}_{\text{sensor}}}{\bar{X}} \times 100 \]

where,

- \( \text{SE}_{\text{sensor}} \) is the standard error of the averaged concentrations of the three sensors during the steady-state period considered
- \( \bar{X} \) is the average concentration measured by the three sensors throughout the same steady-state period

\[ \text{SE}_{\text{sensor}} = \frac{\sqrt{\sum (X_i - \bar{X})^2}}{n} \]

where,

- \( X_i \) is the average value of the three sensors concentrations at different times during the steady-state period considered
- \( \bar{X} \) is the average concentration measured by the three sensors throughout the same steady-state period
Coefficient of Determination (R²)

- Measures the linear relationship between the sensor and the Federal Reference Method (FRM), or Federal Equivalent Method (FEM), or Best Available Technology (BAT) reference instrument
- Lab R² values in these reports are based either on 5-min or 1-hr average data in chamber experiments, under average ambient conditions (20 °C and 40% RH)

\[
\text{Data recovery (\%) } = \frac{N_{\text{valid data}}}{N_{\text{test period}}} \times 100
\]

where,

- \( N_{\text{valid data}} \) is the number of valid sensor data points during the testing period
- \( N_{\text{test period}} \) is the total number of data points for the testing period (from start to end)
A PALAS concentration ramping experiment

5-min mean $PM_{2.5}$ conc. ($\mu g/m^3$)

- GRIMM ($PM_{2.5}$ FEM)
- Sensor_1
- Sensor_2
- Sensor_3

Time (min)
Advantages:

✓ State-of-the-art system designed to systematically evaluate the performance of low-cost sensors

✓ Stable and reproducible PM$_{2.5}$ aerosol atmospheres

✓ Wide range of known target/interferent pollutant concentrations, temperature and relative humidity conditions

✓ Ability for sensor calibration

✓ Sensor data communication options (e.g., external laptop/computer, Ethernet, Wi-Fi, Bluetooth)

Challenges:

• Due to nature of test particles, PM$_{10}$ atmospheres may be less stable

• Sensor performance degradation experiments

• Temperature and RH cycling tests for long periods of time
What’s next for AQ-SPEC?

- Develop methods to test VOC and CH₄ sensors (CA state rule AB 617, South Coast R1180)
- Develop ASTM D22.05 test standard for performance verification of IAQ sensors measuring PM$_{2.5}$ and CO$_2$
- Collaborate in the development of ASTM D22.03 test method for performance evaluation of ambient air quality sensors and other sensor-based instruments
- Calibrate sensors for the various AQMD/AQ-SPEC sensor deployments (e.g., EPA STAR Grant)
- Continue the conversation about a sensor certification/performance verification program
Sensor Performance Verification/Certification Program?

- Which pollutant(s) / sensor type(s)?
  - Are PM (e.g., particle counters) and Ozone (e.g., electrochemical) sensors good candidates?

- “Certified” for which use/application?
  - Regulatory?
  - Permitting?
  - Fenceline?
  - Citizen science?
  - Community monitoring?
  - Other?

- Very expensive to implement correctly
  - Multiple field testing locations across the Nation
  - Multiple laboratory testing facilities
  - Extended testing time
Sensor Deployment Across California
Sensor Data and/or “Sensor” Data

1. Calibration – Factory:
   - Slope/Offset calculations

2. Calibration – Field:
   FEM U.S. EPA/TÜV: Zero-ing and adjustment at start of test

3. Test criteria – Field:
   - Field pre-calibration:
     o Data completeness
     o Long-term drift
     o Between instrument uncertainty
     o Expanded uncertainty
   - No field pre-calibration:
     o Coefficient of determination ($R^2$)

4. Algorithms:
   - Correct interferences (e.g., RH), part of field calibration?
   - AI function:
     o Pre-set and applied during field calibration?
     o Developed, selected, modified during field calibration or evaluation period?

5. Cloud-based systems:
   - Scrape online pollutant or meteorological data from monitoring stations nearby

6. Software upgrades, “over-the-air”:
   - Bug fixes
   - Sensor algorithm changes
   - Sensor level firmware upgrades
   - New functionality
   - New features
   - New calibration

7. ...???
Outline

- Networks of Air Quality Sensors
- Sensor Network Design (3 projects)
  - Identify project goals and air monitoring application
  - Connectivity requirements
  - Hardware selection
  - Data storage, analytics, and visualizations options
- Development of a cloud data management application
Acronyms and Terms

• IoT – Internet of Things
• SaaS – Software as a Service
• PaaS – Platform as a Service
• API – Application Programming Interface

Disclaimer

The South Coast Air Quality Management District does not endorse individual vendors, products or services. Therefore, any reference herein to any vendor, product or services by trade name, trademark, or manufacturer or otherwise does not constitute or imply the endorsement, recommendation or approval of the South Coast Air Quality Management District.
Model for Internet of Things (Air Quality)

Things that Sense:
Air Quality Sensors (Stationary and mobile)
Weather stations, Satellite Remote Sensing

Local Network:
Wi-Fi (Home / Facility), Connected Cars, Bluetooth,
Lo-Ra, Cellular, Zigbee radio network, satellite receiver

Cloud Services:
Data ingestion, transformation, and storage

Analytics:
Web-based analytics, dashboards, and applications
SCAQMD Sensor projects

<table>
<thead>
<tr>
<th>Fence-line monitoring</th>
<th>Regional monitoring network</th>
<th>US EPA STAR grant community monitoring</th>
<th>Future monitoring projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 PM sensors</td>
<td>~ 100 nodes</td>
<td>~ 390 PM sensors in 14 communities</td>
<td>Hotspot identification</td>
</tr>
<tr>
<td>IoT vendor platform</td>
<td>Measures</td>
<td></td>
<td>Mobile monitoring</td>
</tr>
<tr>
<td>Cellular to SaaS</td>
<td>• O$_3$, NO$_2$, &amp; PM</td>
<td>Wi-Fi connected</td>
<td>AB617 community monitoring</td>
</tr>
<tr>
<td>API Access</td>
<td>Cellular to PaaS</td>
<td>Data sent to:</td>
<td>SCAQMD Rule 1180</td>
</tr>
<tr>
<td></td>
<td>API access</td>
<td>• PurpleAir Map</td>
<td>implementation</td>
</tr>
</tbody>
</table>

- US EPA STAR grant community monitoring
  - ~ 390 PM sensors in 14 communities
  - Wi-Fi connected
  - Data sent to:
    - PurpleAir Map
    - AQMD Azure
Fence-line Monitoring
Fence-line Monitoring

- 9 sensors measuring PM
- Wireless connectivity
- Power independence
- Remote Access to data / device

SaaS Cloud Data storage
Web & mobile Application

Data Analytics

Text Alerts
Email Alerts

OPC
Thiamis
Solar Panel & pole mount ~ $120
Alphasense OPC ~ $400
Power Converter ~ $10
Charge Controller ~ $20
IOT Connectivity Hardware ~ $750
Box Vents ~ $10
Enclosure with mounting kit ~ $70
12V Battery ~ $30 $130

$1500 / device
Software as a Service (SaaS): **Environet**
Model for Internet of Things (Air Quality)

Things that Sense:
Air Quality Sensors (Stationary and mobile)
Weather stations, Satellite Remote Sensing

Local Network:
Wi-Fi (Home / Facility), Connected Cars, Bluetooth,
Lo-Ra, Cellular, Zigbee radio network, satellite receiver

Cloud Services:
Data ingestion, transformation, and storage

Analytics:
Web-based analytics, dashboards, and applications

Missing interface and analytics for external Stakeholders
# Fence-line Network Review

<table>
<thead>
<tr>
<th>Decision</th>
<th>Pros</th>
<th>Cons</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 MHz Radio network</td>
<td>Reduced cellular cost</td>
<td>Low Data Recovery</td>
<td>Convert to cellular</td>
</tr>
<tr>
<td>Independent power and connectivity</td>
<td>Not reliant on regulated facility</td>
<td>Initial battery purchase 12V sealed lead acid (SLA)</td>
<td>Convert to Li-ion batteries</td>
</tr>
<tr>
<td>SaaS solution</td>
<td>Fast development with integrating raw sensor to cloud data store</td>
<td>High initial cost for hardware</td>
<td>Use API to access data on an alternative platform</td>
</tr>
<tr>
<td></td>
<td>Customer support for IoT hardware and platform</td>
<td>Ongoing monthly subscription cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Device Management</td>
<td>Limited analytics on SaaS platform</td>
<td></td>
</tr>
</tbody>
</table>
SCAQMD Sensor projects

Fence-line monitoring
- 9 PM sensors
- IoT vendor platform
- Cellular to SaaS
- API Access

Regional monitoring network
- ~ 100 AQY nodes
- Measures:
  - O₃, NO₂, & PM
- Cellular to PaaS
- API access

Community monitoring
- STAR Grant
- ~ 390 PM sensors in 14 communities
- Wi-Fi connected
- Data sent to:
  - Purple Air Map
  - AQMD Azure

Future monitoring projects
- Hotspot identification
- Mobile monitoring
- AB617 community monitoring
- SCAQMD Rule 1180 implementation
Regional Monitoring Network Aims

• Wide-spread deployment across the South Coast Air Basin
  • Connectivity that works in a variety of locations
  • Collaborate with entities that can provide multiple sensor locations
    • School Districts, Cities, Counties, & Libraries

• Wide-spread collocation at reference air monitoring stations
  • Build models for improving sensor performance
  • Understand sensor performance degradation over time

• Good performance in AQ-SPEC evaluation

• Platform as a Service
  • Device management
  • Data management
AQ-SPEC
Air Quality Sensor Performance Evaluation Center

92 instruments in 4 locations
1 - Central Los Angeles (20)
2 - Riverside/San Bernardino (45)
3 - Imperial & Coachella Valley (15)
4 - Catalina Island (4)
• A one week ‘snapshot’ is similar to the 3 month period
• Data Quality Objectives = 90% ($R^2$)
• Correlation not always linear with distance; site location and characteristics also a factor
• How often should the sensor data be corrected using this procedure? Quarterly so far
Inverse distance weighted interpolation

- Higher granularity for maps obtained using sensor data
- Elevated NO\textsubscript{2} along the freeway
- PM\textsubscript{2.5} is more homogeneously distributed throughout the Basin
Aeroqual AQY - Heat map animations
Performance over time: The project has shown PM accumulates on the O₃ sensor inlet mesh over time reducing flow and sensitivity.

O₃ sensor inlet mesh at start mesh after 6 months

Decrease of O₃ sensor sensitivity versus regulatory FEM
## Regional Network Review

<table>
<thead>
<tr>
<th>Decision</th>
<th>Pros</th>
<th>Cons</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular w/ Wi-Fi option</td>
<td>Strong &amp; ubiquitous connectivity</td>
<td>Increase cost</td>
<td>If cellular unavailable, can program for Wi-Fi</td>
</tr>
<tr>
<td>Platform as a Service (PaaS)</td>
<td>Able to create user accounts</td>
<td>Not open source for hardware or data</td>
<td>Stream data to Microsoft Azure and build an alternative platform for front-end web analytics</td>
</tr>
<tr>
<td></td>
<td>Plug-in and sense (No development)</td>
<td>Limited external access</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Device and data management</td>
<td>Limited front-end website visualization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Customer support for IoT hardware and platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collocation</td>
<td>Ability to correct sensor performance drift</td>
<td># of units not providing additional information to network</td>
<td>Worth the cost to provide quality control for sensor measurements</td>
</tr>
</tbody>
</table>
SCAQMD Sensor projects

Fence-line monitoring
- 9 PM sensors
- IoT vendor platform
- Cellular to SaaS
- API Access

Regional Monitoring Network
- ~100 AQY nodes
- Measures: O₃, NO₂, & PM
- Cellular to PaaS
- API access

Community monitoring
- STAR Grant
- ~390 PM sensors in 14 communities
- Wi-Fi connected
- Data sent to:
  - Purple Air Map
  - AQMD Azure

Future monitoring projects
- Hotspot identification
- Mobile monitoring
- AB617 community monitoring
- SCAQMD Rule 1180 implementation
Community Monitoring (US EPA STAR grant)
Engage, Educate, and Empower California Communities on the Use and Applications of “Low-cost” Air Monitoring Sensors

Network Monitoring Aims

• Wide-spread deployment across many communities
  • Connectivity that works at a home
  • Low-Cost: Affordable in the 100s of sensors
  • Ability to be installed, Wi-Fi configured, and registered online by a non-expert
  • Open Source hardware and open data access

• Visualization tool available at start
  • End to End solution (Sensor to Map to Data)
  • Good performance in AQ-SPEC evaluation
## AQ-SPEC

**Air Quality Sensor Performance Evaluation Center**

### PM Sensors

<table>
<thead>
<tr>
<th>Sensor Image</th>
<th>Manufacturer/Model</th>
<th>Type</th>
<th>Pollutant(s)</th>
<th>Approx. Cost (USD)</th>
<th>Yield %</th>
<th>Lab %</th>
<th>Summary Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Image]</td>
<td>Moji China (AirSEQ)</td>
<td>Optical</td>
<td>PM2.5</td>
<td>~$150</td>
<td>R² = 0.80 to 0.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Namco (Panorama)</td>
<td>Electrical</td>
<td>PM (L-DIAL, Large Deposition Surface Area)</td>
<td>~$2,000</td>
<td>PM₂.₅  R² = 0.1</td>
<td>PM₁₀ R² = 0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Origins (Laser Set)</td>
<td>Optical</td>
<td>PM₂.₅ &amp; PM₁₀</td>
<td>~$120</td>
<td>PM₂.₅ R² = 0.80</td>
<td>PM₁₀ R² = 0.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Perkin Elmer (Eye)</td>
<td>Optical</td>
<td>PM</td>
<td>~$5,200</td>
<td>R² = 0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PurpleAir (PA-1, Leko)</td>
<td>Optical</td>
<td>PM₂.₅, PM₁₀, &amp; PM₁₀</td>
<td>~$150</td>
<td>PM₂.₅ R² = 0.93 to 0.97</td>
<td>PM₁₀ R² = 0.97 to 0.97</td>
<td>PM₁₀ R² = 0.97</td>
</tr>
<tr>
<td></td>
<td>PurpleAir (PA-11, Leko)</td>
<td>Optical</td>
<td>PM₂.₅, PM₁₀, &amp; PM₁₀</td>
<td>~$180</td>
<td>PM₂.₅ R² = 0.75</td>
<td>PM₁₀ R² = 0.86 to 0.96</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R13 [MicroP]</td>
<td>Optical</td>
<td>PM₁₀</td>
<td>~$3,000</td>
<td>R² = 0.80 to 0.99</td>
<td>R² = 0.90</td>
<td>PCF (2087.92)</td>
</tr>
<tr>
<td></td>
<td>Subaera (Pure Monitor)</td>
<td>Optical</td>
<td>PM₁₀</td>
<td>~$1,750</td>
<td>R² = 0.73</td>
<td>R² = 0.99</td>
<td>PCF (2087.92)</td>
</tr>
<tr>
<td></td>
<td>Tekneal (PM Evaluation 4.0)</td>
<td>Optical</td>
<td>PM₁₀</td>
<td>~$1,200</td>
<td>R² = 0.80 to 0.96</td>
<td>R² = 0.91</td>
<td>PCF (2100.43)</td>
</tr>
<tr>
<td></td>
<td>Speck</td>
<td>Optical</td>
<td>PM₁₀</td>
<td>~$150</td>
<td>R² = 0.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TSI (AirTraQ)</td>
<td>Optical</td>
<td>PM₁₀</td>
<td>~$1,300</td>
<td>R² = 0.82</td>
<td>R² = 0.90</td>
<td>PCF (2135.83)</td>
</tr>
<tr>
<td></td>
<td>u&gt;Air (Au)</td>
<td>Optical</td>
<td>PM₁₀</td>
<td>~$900</td>
<td>R² = 0.80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### AQ-SPEC Evaluation

**Evaluation Summary**

*Overall, the threePurpleAir PA-1 sensors performed well, compared to the reference monitors for PM₁₀ and PM₂.₅.*

**Field Evaluation Highlights**

- *Overall, the PA-1 sensors performed well, with good agreement with the reference monitors for PM₁₀ and PM₂.₅.*
- *The PA-1 sensors showed high variability compared to the reference monitors for PM₁₀ and PM₂.₅.*
- *The PA-1 sensors showed high variability compared to the reference monitors for PM₁₀ and PM₂.₅.*

**Additional Information**

- *Field evaluation report: [www.aqmd.gov/aqspec](www.aqmd.gov/aqspec)*
- *Lab evaluation report: [www.aqmd.gov/aqspec]*

### Laboratory Evaluation Highlights

- *Sensor's stability and variability were consistent with the reference monitors for PM₁₀ and PM₂.₅.*
- *Good agreement between the reference monitors and the PA-1 sensors was observed.*

---

[www.aqmd.gov/aqspec](www.aqmd.gov/aqspec)
AQ-SPEC
Air Quality Sensor Performance Evaluation Center

www.purpleair.com/map
Community Siting
End User Interface
End User Interface
Hyper-local effects
Missing dashboards for internal users
Need to apply QA/QC methods to create a validated data
Need to apply corrections for sensor performance
# Community Network Review

<table>
<thead>
<tr>
<th>Decision</th>
<th>Pros</th>
<th>Cons</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi-Fi</td>
<td>Free, but local access</td>
<td>New Wi-Fi provider = offline</td>
<td>Keep track and follow up with sensor owners</td>
</tr>
<tr>
<td>Low-cost</td>
<td>Affordability in the 100s</td>
<td>Inexpensive components</td>
<td>Replace power supplies</td>
</tr>
<tr>
<td>End-to-end solution for public</td>
<td>Open source hardware &amp; open data access</td>
<td>Limited internal users. Internal access = same as external OS solution</td>
<td>Work with developer to improve analytics</td>
</tr>
<tr>
<td></td>
<td>Development from sensor to data platform is complete</td>
<td>Limited analytics</td>
<td>Stream data to Microsoft Azure and build an alternative platform</td>
</tr>
<tr>
<td></td>
<td>Customer support for IoT hardware and platform</td>
<td>Not able to customize for individual communities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No Device Management</td>
<td>Data Management</td>
<td></td>
</tr>
</tbody>
</table>
Data Management Platform

Needs Assessment

Multiple sensor and data platforms used for various projects with data in different formats

Data analysis workloads larger than typical tools can handle
  ~ 50 million rows of PurpleAir data and growing
  ~ 44 million rows of Aeroqual data will be generated in 12 months
  ~ 14 million rows of fence-line monitoring data

Limited data analytics available on individual IoT platforms

Limited external user experience with potential confusing user experiences

Need for QA/QC to validate data
Need to apply correction algorithms for sensor performance limitations

Need to quickly visualize and provide results to public in a clear and meaningful manner
Cloud Platform requirements:

- Cloud-based computing platform to ingest, store, analyze, and display data
  - Platform & device agnostic
  - Scalable, secure, and compliant with established data standards

Back End Requirements:

- Manage IoT devices and ingest data
- Perform simple stream analytics
- Process and store geo-spatial time series data
- Store data long-term and scale
- Interface with other platforms (APIs)

Front End Requirements:

- Create and publish web-based interactive dashboards
- Generate positive end-user experiences
Thank you - Questions?

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