Next Generation Air Monitoring (NGAM) - Technology Evaluation and Application Research

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Emerging Technologies Research Program

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Democratization in monitoring is being enabled by……

1. Smartphones with embedded sensors and communications (gps, wifi…)
2. The Internet of Things (IoT) & Cloud Computing
3. Crowd Sourcing and Civic/participatory Science
4. DIY and microelectronics revolution (Arduino, Raspberry Pi…)
5. Desire for personalized & customized information

So where is all this headed?……

1. Weather Underground analogy and digital mutualism (waze app…)
2. State-of-the-Art data assimilation and integration (satellite, sensors, FRM)
3. Robotics, sensors, Cognitive Computing (UAVs)
4. Mobile Health -> Precision Medicine and Epidemiology
5. Exposomics
1. Conducted literature survey on the state of sensor technologies
2. Screened market surveys for commercially-available air sensors
3. Convened workshops to enable dialog among regulators, researchers, device makers, and civic interests
4. Established a Sensor Roadmap by focusing on high priority issues (NAAQS, Air Toxics, Civic participation)
5. Performing technology evaluations on low cost sensors (lab + in-situ)
6. Developing in-house sensor systems (Village Green, CSAM, Spod)
7. Disseminating knowledge to a wide range of stakeholders (sensor developers, users) via user guides and webinars
8. Working with sensor developers to speed up development, improve data quality, establish data standards, and ensure open data access
9. Establishing highly integrated research efforts across EPA and internationally
10. Applying knowledge gained in hands-on sensor deployment activities
<table>
<thead>
<tr>
<th>Air Pollutant of Interest</th>
<th>Useful Detection Limits</th>
<th>Range to Expect</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone (O₃)</td>
<td>10 ppb</td>
<td>0-150 ppb</td>
<td>70 ppb (8 hr)</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>0.1 ppm</td>
<td>0-0.3 ppm</td>
<td>9 ppm (8 hr)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35 ppm (1 hr)</td>
</tr>
<tr>
<td>Sulfur dioxide (SO₂)</td>
<td>10 ppb</td>
<td>0-100 ppb</td>
<td>75 ppb (1 hr)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5 ppm (3 hr)</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO₂)</td>
<td>10 ppb</td>
<td>0-50 ppb</td>
<td>100 ppb (1 hr)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>53 ppb (1 yr)</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>100 ppm</td>
<td>350-600 ppm</td>
<td>None</td>
</tr>
<tr>
<td>Volatile organic compounds (VOCs)</td>
<td>1 μg/m³</td>
<td>5-100 μg/m³ (total VOCs)</td>
<td>None</td>
</tr>
<tr>
<td>Benzene (an example of a VOC and air toxic)</td>
<td>0.01 – 10 μg/m³</td>
<td>0-3 μg/m³</td>
<td>None</td>
</tr>
<tr>
<td>Fine particulate matter (PM₂.₅)</td>
<td>5 μg/m³ (24-hr)</td>
<td>0-40 μg/m³ (24-hr)</td>
<td>35 μg/m³ (24 hr)</td>
</tr>
<tr>
<td>Particulate matter (PM₁₀)</td>
<td>10 μg/m³ (24-hr)</td>
<td>0-100 μg/m³ (24-hr)</td>
<td>12 μg/m³ (1 yr)</td>
</tr>
<tr>
<td>Black carbon (BC)</td>
<td>0.05 μg/m³ (24-hr)</td>
<td>0-15 μg/m³</td>
<td>None</td>
</tr>
</tbody>
</table>
Sensor Types

Metal Oxide (MOS)/Electrochemical and Light Scattering Sensors

- The most widely available of all gas sensor types
- Inexpensive ($15-$300)
- Available in a wide array of pollutants
- Often not specific to any one pollutant
- Co-factors often influence their output
- Response relational to some given parameter

- Light scattering sensors dominate market
- Cost varies ($50-6000)
- Sensitive to RH and stray light
- Size definition varies widely
- Unit output definition varies widely
- Aerosol composition influences response
- Not true mass measurement

Photo credit: http://www.alpha-sense.com/
Example – PM Sensors

DYLOS

SPECK

MET ONE

SHINYEI

AIRBEAM

TZOA
Example – VOC Sensors

UniTech

ToxiRae

EPA VOC
Example – Gas Sensors

- Sensaris
- Air Casting
- Cairclip
- Aeroqual
- AQ Egg
- Node
Example – Multipollutant Stations

ELM

HAZ-SCANNER

AQ MESH
Recent Activities

2012
- ASAP workshop
- Sensors Evaluation and Collaboration

2013
- Regions workshop
- Short-term sensor field tests
- Designing/building autonomous systems: Village Green Project

2014
- Air sensors workshop
- Short-term sensor field tests

2015
- Air Sensors Toolbox
- CSAM-Citizen Science
- Long-term testing: Regional Methods Project - CAIRSENSE
- Sensor network intelligent emissions locator tool (SENTINEL)
- Data visualization: RETIGO
- Community training
- Designing/building autonomous systems: Village Green Project II

Legend:
- Workshops
- Performance testing
- Sensor system build
- Sensor data tools
Ongoing/Planned Activities

2016

AWMA/NACAA/APCA/Tribal Nations/others

Long-term testing: Regional Methods Project - CAIRSENSE

Short-term sensor field tests

Design Citizen Science applications

Designing/building autonomous systems: Village Green Project v. II

Data visualization: RETIGO V2

Sensor network intelligent emissions locator tool (SENTINEL) and advanced S-POD development

2017

Data sharing with stakeholders

Summarize state of the science

New sensor evaluation initiative?

Field Citizen Science applications

Designing/building autonomous systems: Village Green Project v. III

SENTINEL and S-POD advancements

Data visualization: RETIGO V2

Data sharing

Performance testing

Sensor system build

Sensor data tools
EPA’s Recent Community Air Monitoring Training Event

- **Goals:**
  - To share tools, best practices, and resources from EPA’s Air Sensor Toolbox for Citizen Scientists
  - To educate interested groups and individuals on how to conduct successful air monitoring projects
- **30 in-person attendees, 800+ via webinar**
- **Training videos** now available on Air Sensor Toolbox website
- **Ongoing follow-up with Regions/State/Tribal interests**
Sensor Related Resources

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Online Resources Available at:
www2.epa.gov/air-research/air-sensor-toolbox-citizen-scientists

Air Sensor Guidebook
CSAM Operating Procedures
Mobile Sensors & Applications for Air Pollutants
Citizen Science Air Monitor (CSAM): Quality Assurance Guidelines
Evaluation of Field-deployed Low Cost PM Sensors
Critical Peer Reviewed Articles
Defining Emerging Sensor Technology

Sensors and 'Apps' for Community-Based Atmospheric Monitoring

Recent advances in both sensors and wireless communication provide opportunities for improved exposure assessment and increasing community involvement in reducing levels of human exposure to airborne contaminants. These new technologies can enhance data collection to answer scientific and policy questions related to the health and environmental effects of air pollution.
Select Quality Assurance Parameters Involving Continuous Monitoring

- **Bias** - is it routinely high or low with respect to the true value
- **Precision** - how repeatable is the measurement
- **Calibration** - does it respond in a systematic fashion as conc changes
- **Detection limit** - how low and high will it measure successfully
- **Response time** - how fast does the response vary with conc change
- **Linearity of sensor response** - what is the linear or multilinear range
- **Measurement duration** - how much data do you need to collect
- **Measurement frequency** - how many collection periods are needed
- **Data aggregation** - value in aggregating data (1 sec, 1 min, 1 hr, etc)
- **Selectivity/specificity** - does it respond to anything else
- **Interferences** - how does heat, cold, effect response
- **Sensor poisoning and expiration** - how long will the sensor be useful
- **Concentration range** - will the device cover expected highs and lows
- **Drift** - how stable is the response
- **Accuracy of timestamp** - what response output relates to the event
- **Climate susceptibility** - does RH, temp, direct sun, etc impact data
- **Data completeness** - what is the uptime of the sensor
- **Response to loss of power** - what happens when it shuts down

EPA/600/R-14/159 (June 2014)
Direct Collocation with FEMs
Ad-Hoc Testing

- AQMesh: NO₂, NO, O₃, SO₂, CO
- MetOne 831 particle sensor
- Dylos particle sensor
- Air Quality Egg (CO, NO₂, PM, VOCs)
- Aeroqual SM50 O₃ sensor
- Airbeam particle sensor
- Shinyei particle sensor
- Not shown: Cairpol NO₂/O₃ sensor
Opportunity to examine highly varying RH and temperature impacts upon sensor performance
Versus state-operated regulatory monitoring platforms
Correlation matrix (Pearson correlation) of 12-hr average PM between sensors and co-located FEM

Moderate to high correlation between most identical units

Variable correlation with reference ($r = -0.06$ to $0.68$)
Goal: Support community group in using low-cost sensors to explore their air quality

- Designed for use by citizens/students
- Local (on-board) data storage
- Designed for ease of use by non-professionals
- Lessons learned from ORD evaluations integrated into design function (e.g., technology selected / data visualization tools employed)
### ORD-Region research projects using sensors (FY15-16)

<table>
<thead>
<tr>
<th>Project / Year</th>
<th>Regional Partner(s)</th>
<th>Measurements</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAIRSENSE (ongoing)</td>
<td>Region 1 Region 4 Region 5 Region 7 Region 8</td>
<td>PM, ozone, nitrogen dioxide – four sensor nodes</td>
<td>Atlanta, GA</td>
</tr>
<tr>
<td>CSAM (Being summarized)</td>
<td>Region 2</td>
<td>PM, NO₂, temperature, humidity – portable stations</td>
<td>Ironbound community, NJ</td>
</tr>
<tr>
<td>CitySpace (Under development)</td>
<td>Region 4 Region 6 Region 7</td>
<td>PM – up to 20 stationary nodes</td>
<td>Memphis, TN</td>
</tr>
<tr>
<td>AirMapper (Under development)</td>
<td>Region 5 Region 10</td>
<td>PM, noise, temperature, humidity – portable units</td>
<td>Chicago, IL Portland, OR</td>
</tr>
<tr>
<td>Puerto Rico EJ (Under development)</td>
<td>Region 2</td>
<td>Tentative: PM, VOCs, NO₂ – portable units</td>
<td>Puerto Rico</td>
</tr>
</tbody>
</table>
## Possible Sensor Tiers

<table>
<thead>
<tr>
<th>Tier</th>
<th>Application Area</th>
<th>Precision and Bias Error</th>
<th>Data Completeness*</th>
<th>Rationale (Tier I-IV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Education and Information</td>
<td>&lt;50%</td>
<td>≥ 50%</td>
<td>Measurement error is not as important as simply demonstrating that the pollutant exists in some wide range of concentration.</td>
</tr>
<tr>
<td>II</td>
<td>Hotspot Identification and Characterization</td>
<td>&lt;30%</td>
<td>≥ 75%</td>
<td>Higher data quality is needed here to ensure that not only does the pollutant of interest exist in the local atmosphere, but also at a concentration that is close to its true value.</td>
</tr>
<tr>
<td>III</td>
<td>Supplemental Monitoring</td>
<td>&lt;20%</td>
<td>≥ 80%</td>
<td>Supplemental monitoring might have value in potentially providing additional air quality data to complement existing monitors. To be useful in providing such complementary data, it must be of sufficient quality to ensure that the additional information is helping to “fill in” monitoring gaps rather than making the situation less understood.</td>
</tr>
<tr>
<td>IV</td>
<td>Personal Exposure</td>
<td>&lt;30%</td>
<td>≥ 80%</td>
<td>Many factors can influence personal exposures to air pollutants. Precision and bias errors suggested here are representative of those reported in the scientific literature under a variety of circumstances. Error rates higher than these make it difficult to understand how, when, and why personal exposures have occurred.</td>
</tr>
</tbody>
</table>
Data Visualization Tools-RETIGO

- Free, on-line data visualization tool for spatially resolved air quality measurements
- Designed for plug and play data handling scenarios
- Provides time and spatial features of your dataset
- On-line tutorials provide step by step user instructions
- Available at http://www.epa.gov/hesc/real-time-geospatial-data-viewer
Village Green Project

- Prototype located in North Carolina, USA outside of a public library
- Self-contained system incorporates
  - power supply: solar panels & battery
  - microprocessor
  - cellular modem
- Measures two common air pollutants
  - ozone and fine particulate matter (PM$_{2.5}$, particle diameter ≤ 2.5 µm)
- Measures weather
  - wind speed and direction
  - temperature and humidity
- Sampling rate – every minute
- Comparable results
  - Instruments agreed within 10 – 20 % of reference monitors located nearby
- Prototype design made available:
  http://pubs.acs.org/doi/suppl/10.1021/ac...
New Village Green Pilot Project

Partners: City of Philadelphia, National Park Service

Partners: State of Kansas, Wyandotte County, School District

Partners: District Department of the Environment, Smithsonian

Partners: State of Oklahoma, Myriad Botanical Gardens
Village Green Project: data website

Data website: Interactive data exploration
Mid-Tier VOC Research Efforts

• High demand by wide range of stakeholders for continuous VOC monitoring with lower operational costs
• EPA investigating low cost as well as mid-tier ($5-10K) technologies to define the state of the science and how they might be applied
Automated work truck sensors

In-plant / Work Truck

Simplified GMAP OTM 33

benzene leak

Wind
• We have examined and continue to examine sensors as they become available.
• Working closely nationally with South Coast and internationally with the EU
• We are integrating these technologies into a variety of research projects
• Investigating lower cost (< $2500) as well as mid-tier ($3000-$10000) sensors
• Wide range in capabilities. Cost is not necessarily the driver in performance.
• Low cost sensor performance is as follows Ozone>PM> CO> NO2>SO2
• Very limited low cost options for toxics, VOCs, ammonia, hydrogen sulfide, methane
• Source monitoring efforts like the SENTINEL and S-PODs are highly promising
• New data visualization tools like RETIGO are now available for use
• Village Green Project giving EPA/Regions/Communities immediate access to continuous environmental data using sustainable technology
• Demand to understand this technology sector is only increasing in intensity
• Health messaging from high frequency data is a BIG issue
• Application requirements determine data quality needs and thus instrumentation
• Working with device makers on establishing data standards
Thank You

One resource for you is the following website:
(http://www2.epa.gov/air-research/air-sensor-toolbox-citizen-scientists)