AQ-SPEC
Air Quality Sensor Performance Evaluation Center

# Evaluation of "Low-cost" Sensors for Measuring Gaseous and Particle Air Pollutants: Results from Three Years of Field and Laboratory Testing

*Andrea Polidori, Ph.D.*
*Atmospheric Measurements Manager*

*South Coast Air Quality Management District*
*Diamond Bar, CA*

Cumulative Impacts and Community Vulnerability Symposium
Diamond Bar; July 27, 2017

# Low-Cost Air Quality Sensors

- Rapidly proliferating
- Tremendous potential
  - Low-cost
  - Ease of use
- Multiple potential applications
  - Spatial/Temporal air quality info
  - Fence-line applications
  - Regulatory/Academic/Citizen scientist
- *How reliable/accurate are they??*
- *Need to systematically evaluate their performance*


EPA Village Green Project

# Background

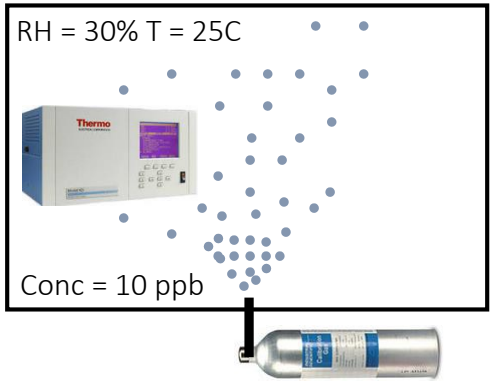
- Established in July 2014
- Over $600,000 investment
- Main Goals & Objectives
  - Provide guidance & clarity for ever-evolving sensor technology
  - Catalyze successful evolution/use of sensor technology
  - Minimize confusion
- Sensor Selection Criteria
  - Commercially available
    - *Optical*
    - *Electrochemical*
    - *Metal oxide*
  - Real- or near-real time
  - Criteria pollutants & air toxics

# Overview

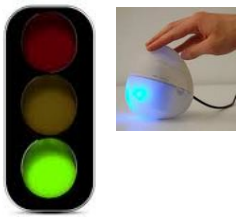
## FIELD TESTING
(Side-by-side comparison with FRMs)

VS

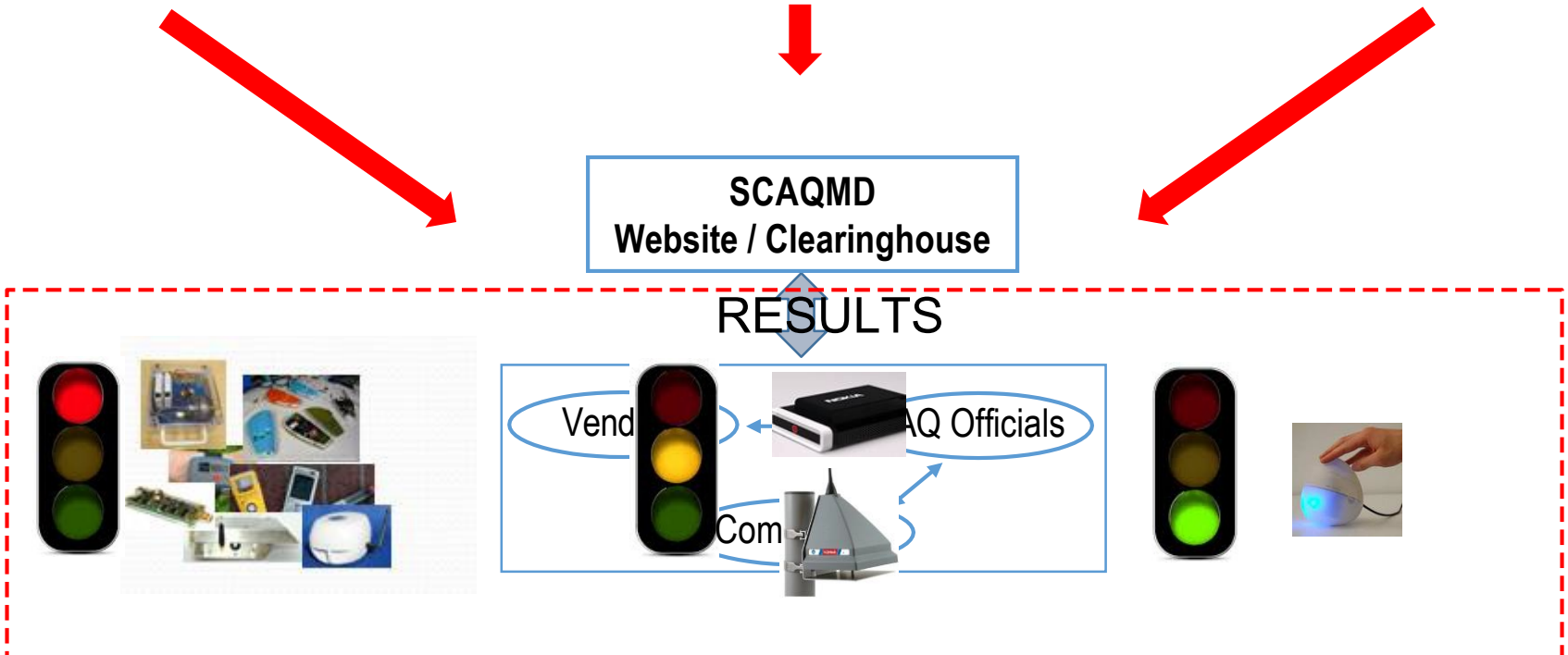
## LAB TESTING
(Controlled conditions)




## RESULTS
(Categorize sensors based on performance)



# Overview (cont.)



# Field Testing

- Started on 09/12/2014
  - Sensor tested in triplicates
  - Two month deployment
  - < ~ $2,000: purchase
  - > ~ $2,000: lease or borrow

- Locations:
  - Rubidoux station (main)
    - Inland site
    - Fully instrumented
  - I-710 station
    - Near-roadway site
    - Fully instrumented

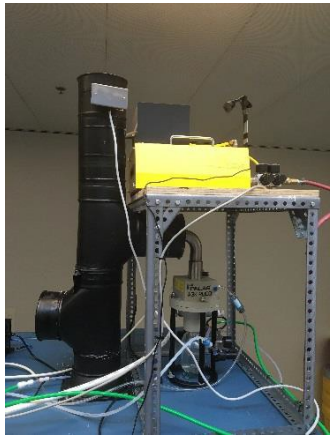
# AQ-SPEC

Air Quality Sensor Performance Evaluation Center

South Coast AQMD

## Laboratory Testing

### Aerosol Test




### Gas Test

# Laboratory Testing (cont.)

T and RH controlled: T (0-50 ˚C); RH (5-95%)

## Particle testing

- Particle generation systems
- Particle monitors: mass concentration and size distribution

## Gas testing

- Gas generation / dilution system
- Gas monitors: CO, $NO_X$, $O_3$, $SO_2$, $H_2S$, $CH_4$/NMHC

# AQ-SPEC Homepage

South Coast AQMD

Home
Sensors
Evaluations
Research Projects
Resources
Workshops
Sensor News
About Us
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South Coast *Air Quality Management District*

## AQ-SPEC

Air Quality Sensor Performance Evaluation Center


**Recently added/updated:**

- Summary Evaluation Reports (posted, 01/17/17)
- Shinyei PM Eval Kit - Lab Evaluation (posted, 01/17/17)
- Purple Air PA-I - Lab Evaluation (posted, 01/11/17)
- 2B Technologies POM - Lab Evaluation (posted, 01/06/17)
- UNITEC SENS-IT CO - Lab Evaluation (posted, 01/06/17)
- New article by Kelly et al. at University of Utah (posted, 01/06/17)
- New article by Deng et al. at Arizona State University (posted, 01/06/17)

### Background

In an effort to inform the general public about the actual performance of commercially available "low-cost" air quality sensors, the SCAQMD has established the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) program. The AQ-SPEC program aims at performing a thorough characterization of currently available "low-cost" sensors under ambient (field) and controlled (laboratory) conditions.

### Main Goals & Objectives

- Evaluate the performance of commercially available "low-cost" air quality sensors in both field and laboratory settings
- Provide guidance and clarity for ever-evolving sensor technology and data interpretation
- Catalyze the successful evolution, development, and use of sensor technology

### Sensor Selection Criteria

- The sensor shall have potential for near-term use.
- The sensor shall provide real- or near-real time measurements.
- The sensor shall measure one or more of the National Ambient Air Quality Standards (NAAQS) criteria pollutants, air toxics, pollutants of concern and non- air toxics. Examples of the targeted gases and particles are carbon monoxide (CO), ozone ($O_3$), nitrogen oxides ($NO_x$), particulate matter (PM), volatile organic compounds (VOCs), hydrogen sulfide ($H_2S$) and methane ($CH_4$).
- The market cost of the sensor shall be less than $2,000.
- Turnkey products will be tested first.

### Why did SCAQMD create the AQ-SPEC Program?

# AQ-SPEC Homepage (cont.)


# PM Sensors

| Sensor Image | Manufacturer (Model) | Type | Pollutant(s) | Approx. Cost (USD) | *Field $R^2$ | *Lab $R^2$ | Summary Report |
|---|---|---|---|---|---|---|---|
|  | **AethLabs** (microAeth) | Optical | BC (Black Carbon) | ~$6,500 | $R^2$ ~ 0.79 to 0.94 | | |
|  | **Air Quality Egg** (Version 1) | Optical | PM | ~$200 | $R^2$ ~ 0.0 | | |
|  | **Air Quality Egg** (Version 2) | Optical | PM | ~$240 | $PM_{2.5}$: $R^2$ ~ 0.79 to 0.85<br>$PM_{10}$: $R^2$ ~ 0.31 to 0.40 | | |
|  | **Alphasense** (OPC-N2) | Optical | $PM_{1.0}$, $PM_{2.5}$ & $PM_{10}$ | ~$450 | $PM_{1.0}$: $R^2$ ~ 0.63 to 0.82<br>$PM_{2.5}$: $R^2$ ~ 0.38 to 0.80<br>$PM_{10}$: $R^2$ ~ 0.41 to 0.60 | $R^2$ ~ 0.99 | PDF (1,291 KB) |
|  | **Dylos** (DC1100) | Optical | $PM_{(0.5-2.5)}$ | ~$300 | $R^2$ ~ 0.65 to 0.85 | $R^2$ ~ 0.89 | PDF (1,384 KB) |
|  | **Foobot** | Optical | $PM_{2.5}$ | ~$200 | $R^2$ ~ 0.55 | | |
|  | **HabitatMap** (AirBeam) | Optical | $PM_{2.5}$ | ~$200 | $R^2$ ~ 0.65 to 0.70 | $R^2$ ~ 0.87 | PDF (1,144 KB) |
|  | **Hanvon** (Hanvon N1) | Optical | $PM_{2.5}$ | ~$200 | $R^2$ ~ 0.52 to 0.79 | | |
|  | **MetOne** (Neighborhood Monitor) | Optical | $PM_{2.5}$ | ~$1,900 | $R^2$ ~ 0.53 to 0.67 | | |
|  | **Moji China** (Airnut) | Optical | $PM_{2.5}$ | ~$150 | $R^2$ ~ 0.81 to 0.88 | | |
|  | **Naneos** (Partector) | Electrical | PM (LDSA: Lung-Deposited Surface Area) | ~$7,000 | $PM_{1.0}$: $R^2$ ~ 0.1<br>$PM_{2.5}$: $R^2$ ~ 0.2 | | |
|  | **Origins** (Laser Egg) | Optical | $PM_{2.5}$ & $PM_{10}$ | ~$200 | $PM_{2.5}$: $R^2$ ~ 0.58<br>$PM_{10}$: $R^2$ ~ 0.0 | | |
|  | **Perkin Elmer** (ELM) | Optical | PM | ~$5,200 | $R^2$ ~ 0.0 | | |
|  | **PurpleAir (PA-I)** | Optical | $PM_{1.0}$, $PM_{2.5}$ & $PM_{10}$ | ~$150 | $PM_{1.0}$: $R^2$ ~ 0.93 to 0.95<br>$PM_{2.5}$: $R^2$ ~ 0.77 to 0.92<br>$PM_{10}$: $R^2$ ~ 0.32 to 0.44 | $PM_{1.0}$: $R^2$ ~ 0.95<br>$PM_{2.5}$: $R^2$ ~ 0.99<br>$PM_{10}$: $R^2$ ~ 0.97 | PDF (1,072 KB) |
|  | **PurpleAir (PA-II)** | Optical | $PM_{1.0}$, $PM_{2.5}$ & $PM_{10}$ | ~$200 | $PM_{1.0}$: $R^2$ ~ 0.96 to 0.98<br>$PM_{2.5}$: $R^2$ ~ 0.93 to 0.97<br>$PM_{10}$: $R^2$ ~ 0.66 to 0.70 | | |
|  | **RTI** (MicroPEM) | Optical | $PM_{2.5}$ | ~$2,000 | $R^2$ ~ 0.65 to 0.90 | $R^2$ ~ 0.99 | PDF (1,087 KB) |
|  | **Shinyei** (PM Evaluation Kit) | Optical | $PM_{2.5}$ | ~$1,000 | $R^2$ ~ 0.80 to 0.90 | $R^2$ ~ 0.93 | PDF (1,156 KB) |
|  | **Speck** | Optical | $PM_{2.5}$ | ~$150 | $R^2$ ~ 0.32 | | |
|  | **TSI** (AirAssure) | Optical | $PM_{2.5}$ | ~$1,500 | $R^2$ ~ 0.82 | | |

# Results

<u>Most PM sensors showed</u>:

- Minimal down time
- Moderate intra-model variability
- Strong correlation ($R^2$) with FEMs

<u>However…</u>

- Sensor "calibration" is needed in most cases
- Very small particles (e.g. < 0.5 micrometers) are not detected
- Bias in algorithms used to convert particle counts to particle mass

# Gaseous Sensors

| Sensor Image | Manufacturer (Model) | Type | Pollutant(s) | Approx. Cost (USD) | *Field $R^2$ | *Lab $R^2$ | Summary Report |
|---|---|---|---|---|---|---|---|
|  | **2B Technologies** (POM) | UV absorption (FEM Method) | $O_3$ | ~$4,500 | $R^2$ ~ 1.00 | $R^2$ ~ 0.99 | PDF (1,295 KB) |
|  | **Aeroqual** (S-500) | Metal Oxide | $O_3$ | ~$500 | $R^2$ ~ 0.85 | | |
|  | **Air Quality Egg** (Version 1) | Metal Oxide | CO, $NO_2$ & $O_3$ | ~$200 | CO: $R^2$ ~ 0.0<br>$NO_2$: $R^2$ ~ 0.40<br>$O_3$: $R^2$ ~ 0.85 | | |
|  | **Air Quality Egg** (Version 2) | Electrochem | CO & $NO_2$ | ~$240 | CO: $R^2$ ~ 0.0<br>$NO_2$: $R^2$ ~ 0.0 | | |
|  | **Air Quality Egg** (Version 2) | Electrochem | $O_3$ & $SO_2$ | ~$240 | $O_3$:<br>$R^2$ ~ 0.0 to 0.20<br>$SO_2$: $R^2$ n/a | | |
|  | **AQMesh** (v.4.0) (Discontinued) | Electrochem | CO, NO, $NO_2$ & $O_3$ | ~$10,000 | CO:<br>$R^2$ ~ 0.42 to 0.80<br>NO:<br>$R^2$ ~ 0.0 to 0.44<br>$NO_2$:<br>$R^2$ ~ 0.0 to 0.46<br>$O_3$:<br>$R^2$ ~ 0.46 to 0.83 | | |
|  | **Perkin Elmer** (ELM) | Metal Oxide | NO, $NO_2$ & $O_3$ | ~$5,200 | NO: $R^2$ n/a<br>$NO_2$: $R^2$ ~ 0.0<br>$O_3$:<br>$R^2$ ~ 0.89 to 0.96 | | |
|  | **Smart Citizen Kit** | Metal Oxide | CO, $NO_2$ | ~$200 | CO:<br>$R^2$ ~ 0.50 to 0.85<br>$NO_2$: $R^2$ ~0.0 | | |
|  | **Spec Sensors** | Electrochem | CO, $NO_2$ & $O_3$ | ~$500 | CO:<br>$R^2$ ~ 0.84 to 0.90<br>$NO_2$:<br>$R^2$ ~ 0.0 to 0.16<br>$O_3$:<br>$R^2$ ~ 0.0 to 0.24 | | |
|  | **UNITEC** (SENS-IT) | Metal Oxide | CO, $NO_2$ & $O_3$ | ~$2,200 | CO:<br>$R^2$ ~ 0.33 to 0.43<br>$NO_2$:<br>$R^2$ ~ 0.60 to 0.65<br>$O_3$:<br>$R^2$ ~ 0.72 to 0.83 | CO:<br>$R^2$ ~ 0.99<br>$O_3$:<br>$R^2$ ~ 0.82 to 0.90 | CO: PDF (1,283 KB)<br>$O_3$: PDF (1,177 KB) |

# Results (cont.)

<u>Most gaseous sensors showed</u>:

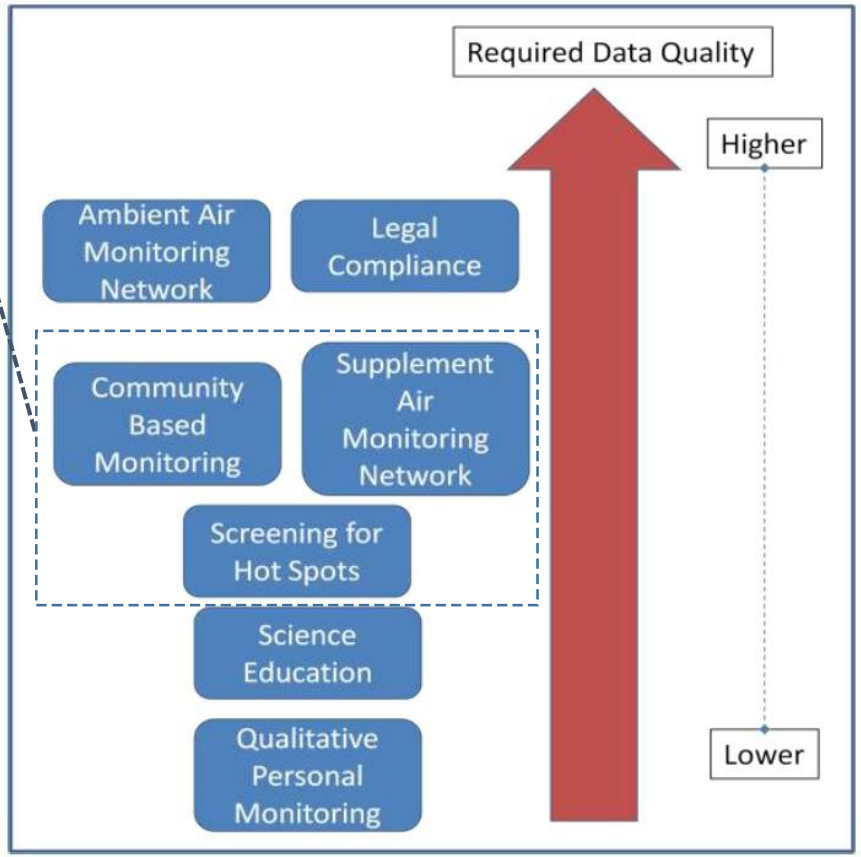
- Acceptable data recovery
- Wide intra-model variability range
- CO; NO; $O_3$ (when measured alone): good correlation with FRMs
- $O_3$ + $NO_2$: low correlation with FRM (potential $O_3$/$NO_2$ interference)
- $SO_2$; $H_2S$; VOC: difficult to measure with available sensors

# Sensor Applications

- Categorize sensors based on performance
- Identify application(s) based on sensor capabilities

Several interesting applications

- Characterize spatial variations
  - Wide area coverage
- Improve network design
  - Set-up monitors in high concentration areas
- Permitting
  - Monitoring before and after construction
- Fence-line Monitoring
  - Large refineries and emission sources
- Community concerns
  - Local impact of freeways, airports, refineries, etc.




EPA's "*DRAFT Roadmap for Next Generation Air Monitoring*"

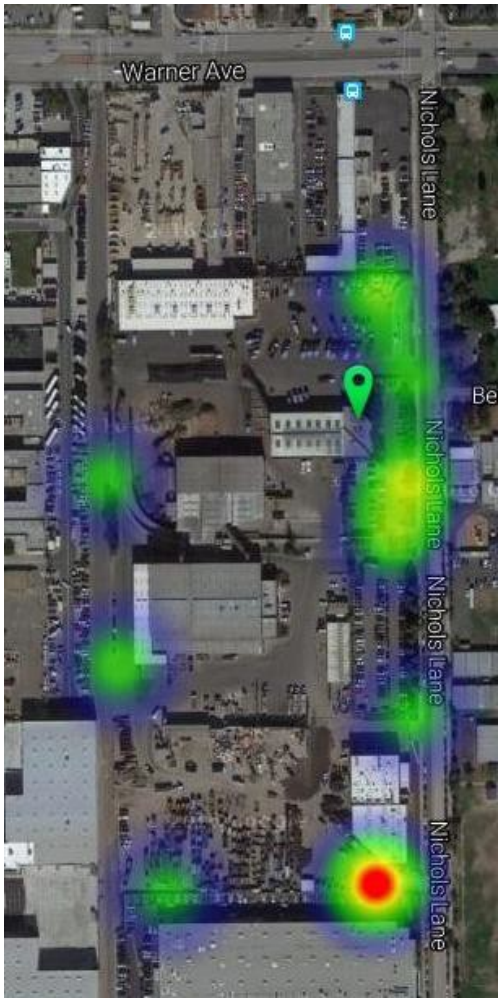
# Current SCAQMD Activities

## Sensor Network: Pilot Study #1

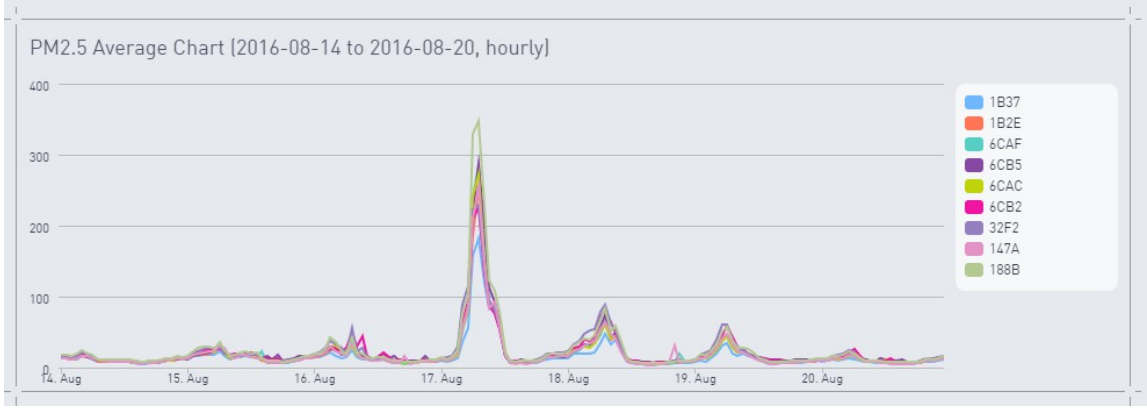

- Monitor fugitive emissions from a Waste Disposal facility in Southern California
- 9 sensor nodes deployed at facility fence-line in June 2016
- Wireless network / remote server
- Real-time $PM_1$, $PM_{2.5}$ and $PM_{10}$ monitoring

# Current SCAQMD Activities (cont.)

## Sensor Network: Pilot Study #1

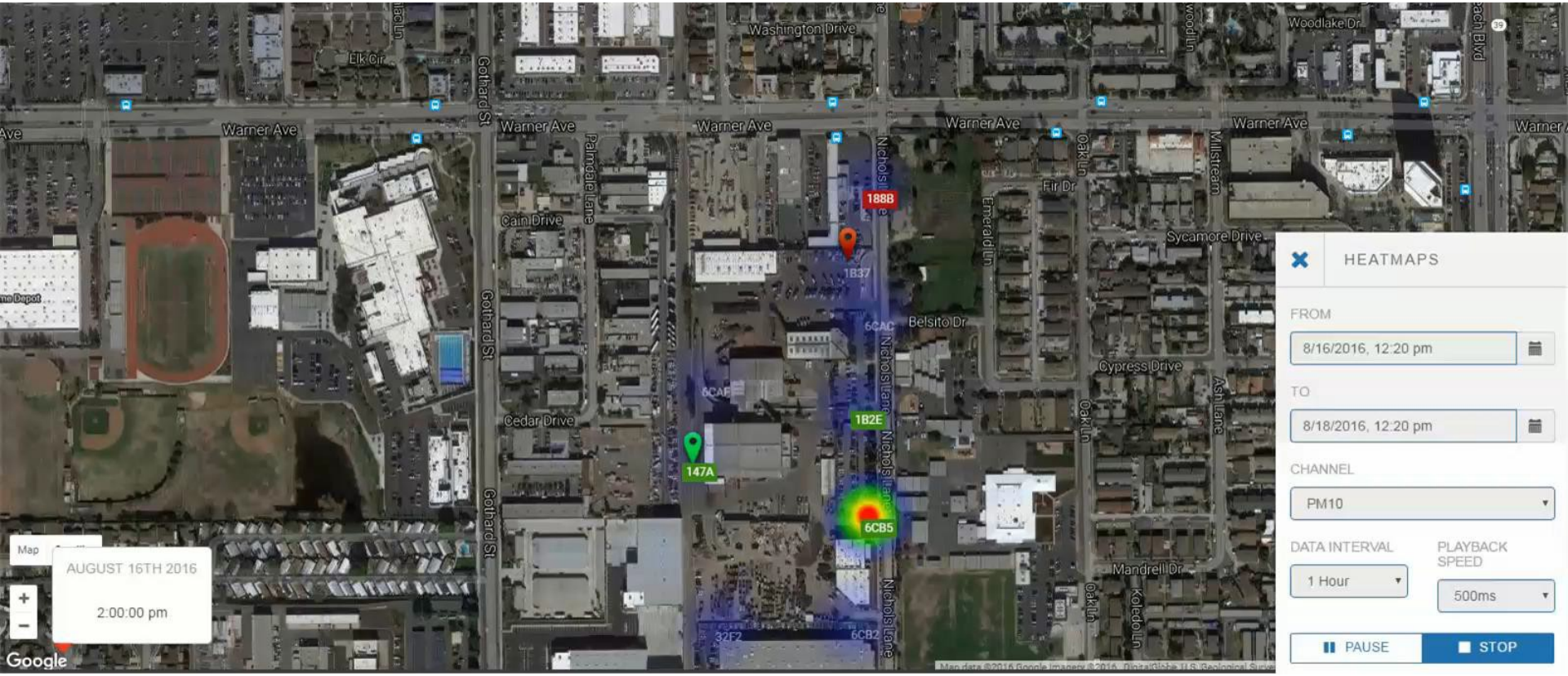



- Dedicated website
  - [www.aqmd.meshify.com](http://www.aqmd.meshify.com)
  - *Real-time data logging, display, and mapping*
  - *Data analytics*
  - *Email and/or text alerts*
- Project benefits
  - *Correlate PM measurements with on-site activities*
  - *Measure PM levels before and after facility upgrades*



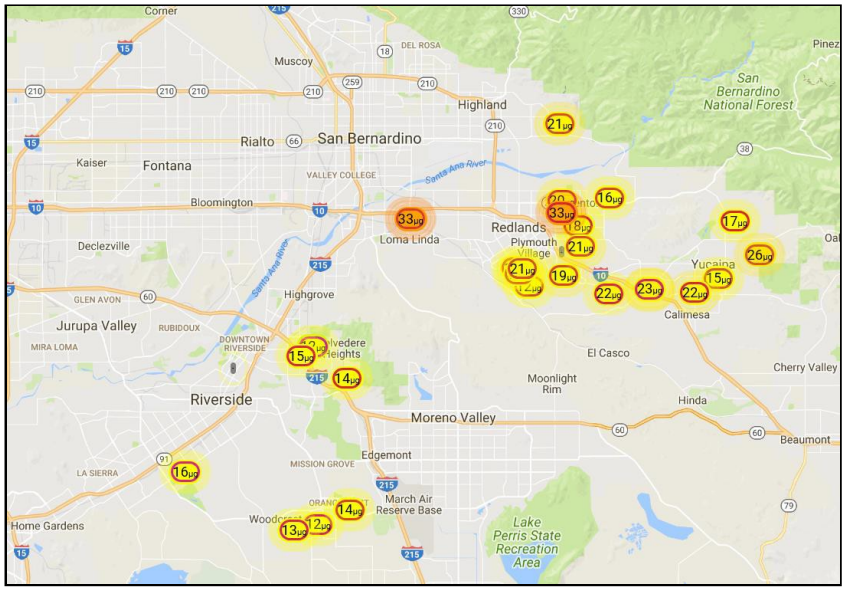
# Current SCAQMD Activities (cont.)

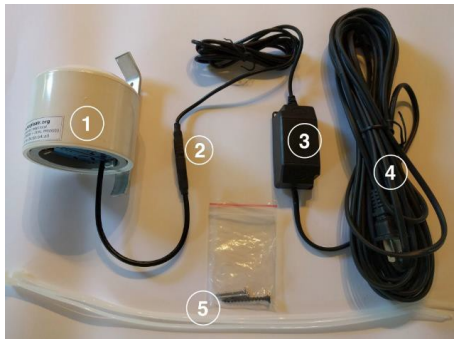
## Sensor Network: Pilot Study #1



# Current SCAQMD Activities (cont.)

## Sensor Network: Pilot Study #2




- 31 “low-cost” PM sensors deployed in the Redlands, CA area
- Real-time $PM_1$, $PM_{2.5}$ and $PM_{10}$ monitoring
- Wireless network / remote server
  - *Sensor device/data management: Microsoft Azure IoT + Power Bi*
- Project goals
  - *Test sensor durability*
  - *Show ability to scale up in near future*
  - *Help improve accuracy of satellite data*

# Current SCAQMD Activities (cont.)

## Community Scale Study (EPA Grant)

- Use "SPODs" to:
  - *Monitor VOC emissions from refineries in real-time*
  - *Assess potential impacts on nearby communities*
  - *Study temporal and spatial dispersion of VOCs*

  *(Technology: PID sensor + 2D anemometer)*

- Use of Optical Remote Sensing (ORS) methods to:
  - *Validate "SPOD" data*
  - *Estimate annual refinery (VOC) emissions*

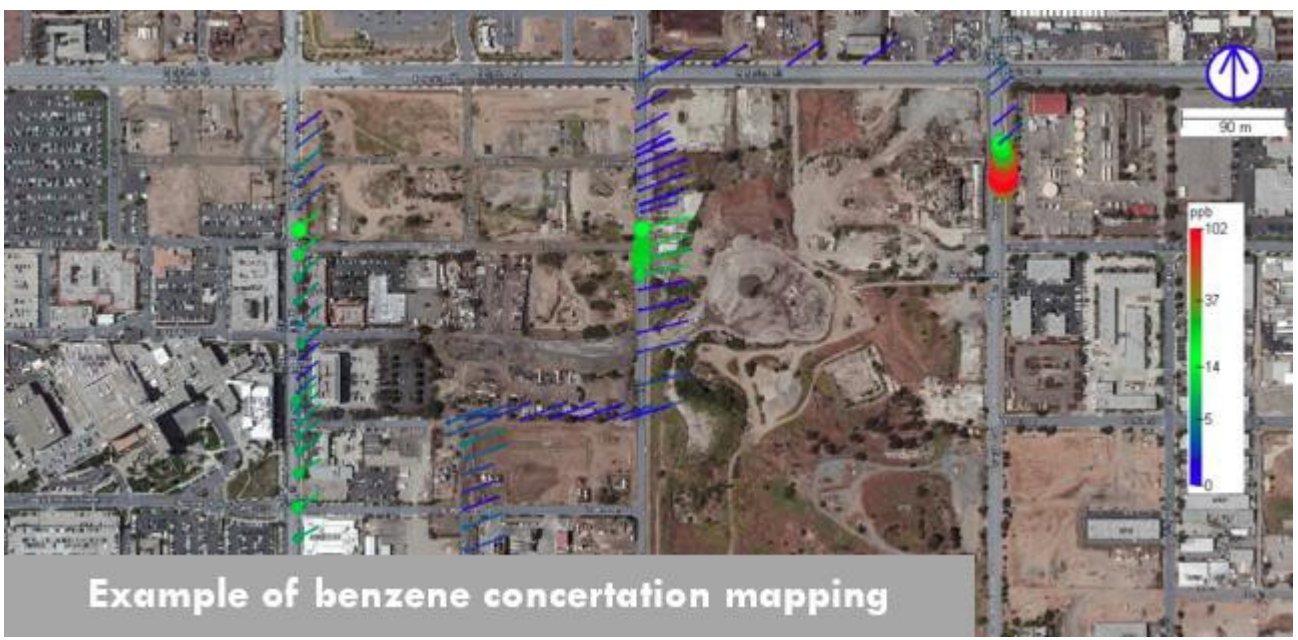
  *(Technology: SOF/DOAS/FTIR)*


# Current SCAQMD Activities (cont.)

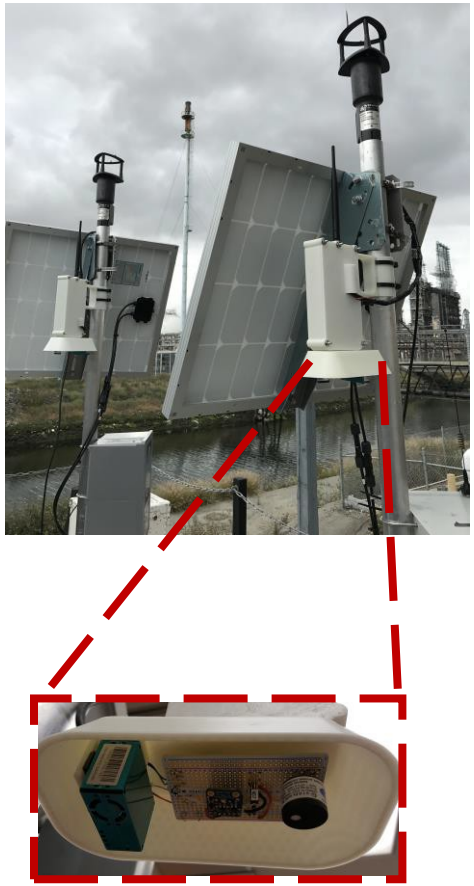
## Community Scale Study (EPA Grant)

- Mobile ORS: *quarterly surveys of emission measurements and concentrations mapping*

- "Low-cost" sensors network: *long-term monitoring of VOC and PM2.5 at facility fence-line and inside communities*

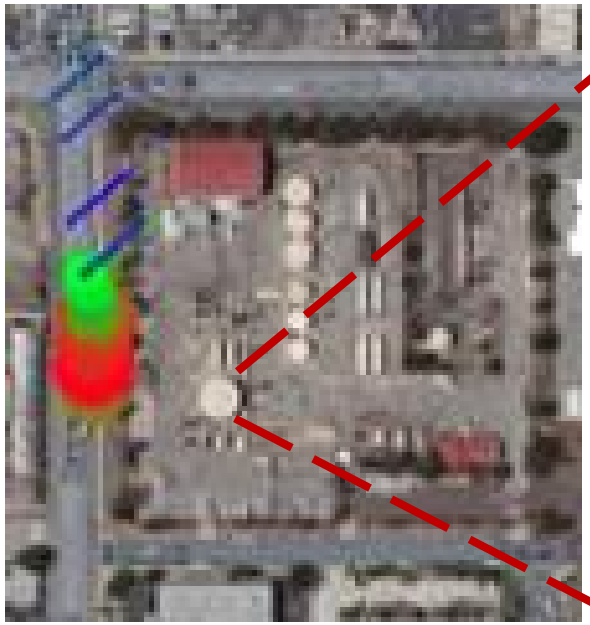



Example of benzene concertation mapping



# Current SCAQMD Activities (cont.)

## Community Scale Study (EPA Grant)



# Current SCAQMD Activities (cont.)

## U.S. EPA Science To Achieve Results (STAR) project

- Provide California communities with the knowledge necessary to select, use and maintain low-cost sensors and to correctly interpret the collected data

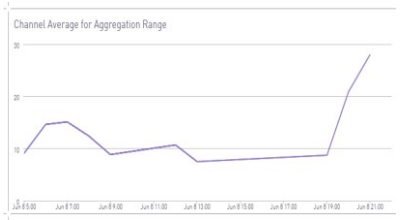
- Four specific aims:
  - #1: Develop educational material for communities
  - #2: Evaluate / identify candidate sensors for deployment
  - #3: Deploy selected sensors in California communities
  - #4: Communicate the lessons learned to the public

- Three year study in collaboration with:
  - University of California Los Angeles (UCLA; Co-PI)
  - Sonoma Technology Inc. (STI; Co-PI)
  - BAAQMD
  - Santa Barbara County APCD
  - Community Groups
  - Weather Underground
  - University of Auckland (New Zealand)

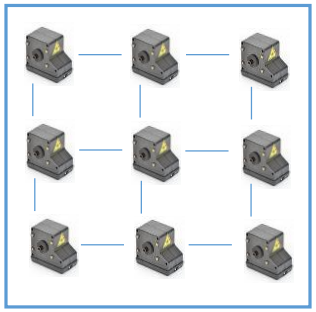

- 6 selected CA communities
- EJ areas
- 200+ subjects
- > 150 sensors

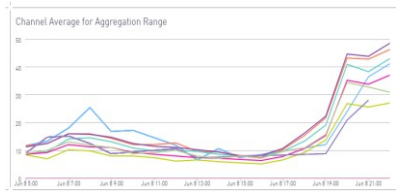
# Low-cost Sensors / High-cost Networks

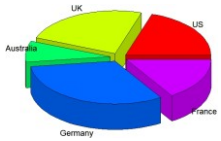
- Single user (e.g. 1 sensor)
  - Cost: $
    - Hardware
    - Minimal maintenance



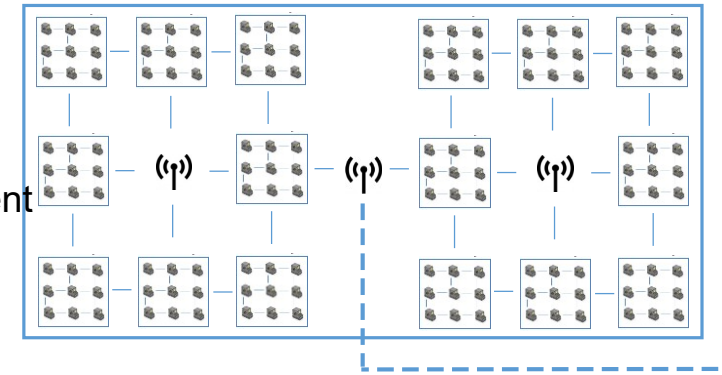

- Small sensor network (e.g. 9 sensors)
  - Cost: $$
    - Hardware
    - Maintenance & calibration
    - Sensor connectivity
    - Data logging and management
    - Data validation and analysis
    - Visualization and reporting

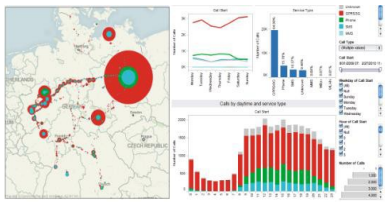


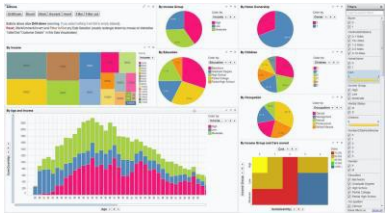



- Large sensor network (e.g. > 100 sensors)
  - Cost: $$$$
    - Hardware
    - Maintenance & calibration
    - Sensor connectivity
    - Data logging and management
    - Data validation and analysis
    - Visualization and reporting







# "Making Sense of Sensors"
# September 27-28, 2017

The South Coast Air Quality Management District (SCAQMD) and the California Air Pollution Control Officers Association (CAPCOA) invite you to attend the "Making Sense of Sensors" Conference, which will be held **Wednesday and Thursday, September 27-28, 2017,** in Diamond Bar, CA. This networking conference will gather experts from government, academia, environmental and research organizations, and the industry to learn and share the latest information on air quality sensors. All participants will have an opportunity to tour the AQ-SPEC Testing Center.

**Topics will include:**

- State of sensor technology, data quality and applications
- Sensor network development
- Validation, analysis and interpretation of sensor data
- Stakeholders' perspectives and expectations
- Sensor data dissemination

.....and more

**Where:**

South Coast AQMD Headquarters
21865 Copley Drive
Diamond Bar, California 91765

For more information, visit www.aqmd.gov/aq-spec or www.capcoa.org. To sign up to receive electronic updates on the upcoming event, go to www.aqmd.gov/sign-up, enter your name and email, scroll down to New Technology, and click the box next to AQ-SPEC and/or Technology Forums.

For sponsor and exhibit opportunities, please contact Ms. Drue Hargis at (909) 396-3237 or by email at dhargis@aqmd.gov.

## September 27-28, 2017 at SCAQMD Headquarters

21865 Copley Dr. Diamond Bar, CA 91765

Stay Connected @SouthCoastAQMD

AQ-SPEC
Air Quality Sensor Performance Evaluation Center

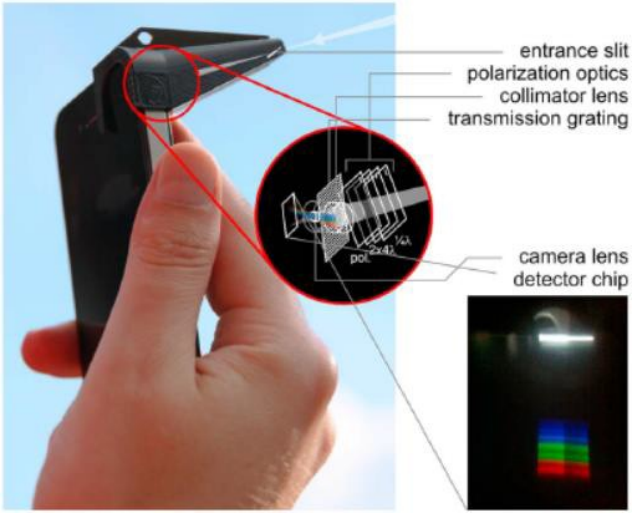
# Thanks!

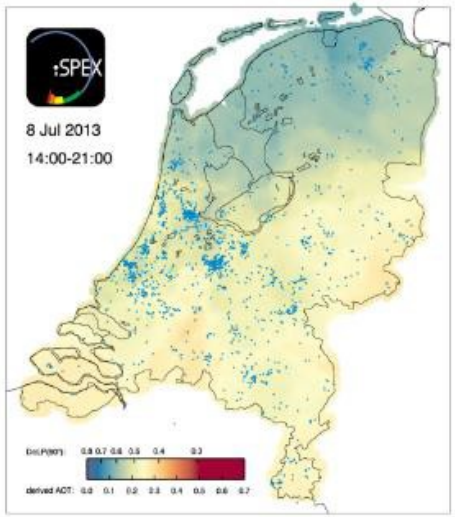
The AQ-SPEC Team

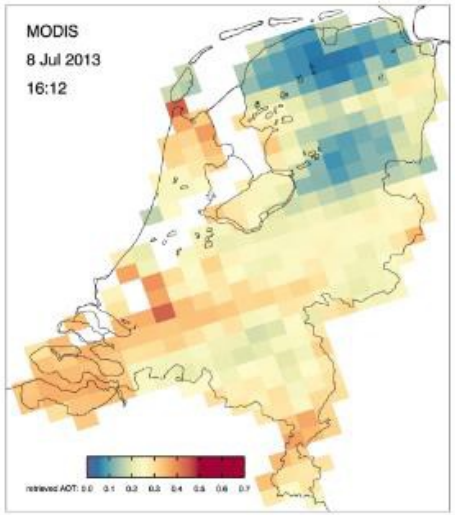
- *Dr. Andrea Polidori*
- *Dr. Vasileios Papapostolou*
- *Brandon Feenstra*
- *Dr. Hang Zhang*
- *Berj Der Boghossian*
- *Dr. Olga Pickelnaya*

# Sensor Network Example - iSPEX

- Relatively cheap and inaccurate sensors can provide useful information when used appropriately
- iSPEX
  - ~$4 add-on for smart-phone cameras
  - Measures Aerosol Optical Thickness to estimate atmospheric aerosols!!!
  - Daytime, cloud-free measurements only
  - Project led by Frans Snik, Leiden University (Netherlands)




- Thousands of (free) iSPEX used to for three days in 2013
- Results comparable to ground-based, network, and satellite measurements

iSPEX Homepage