



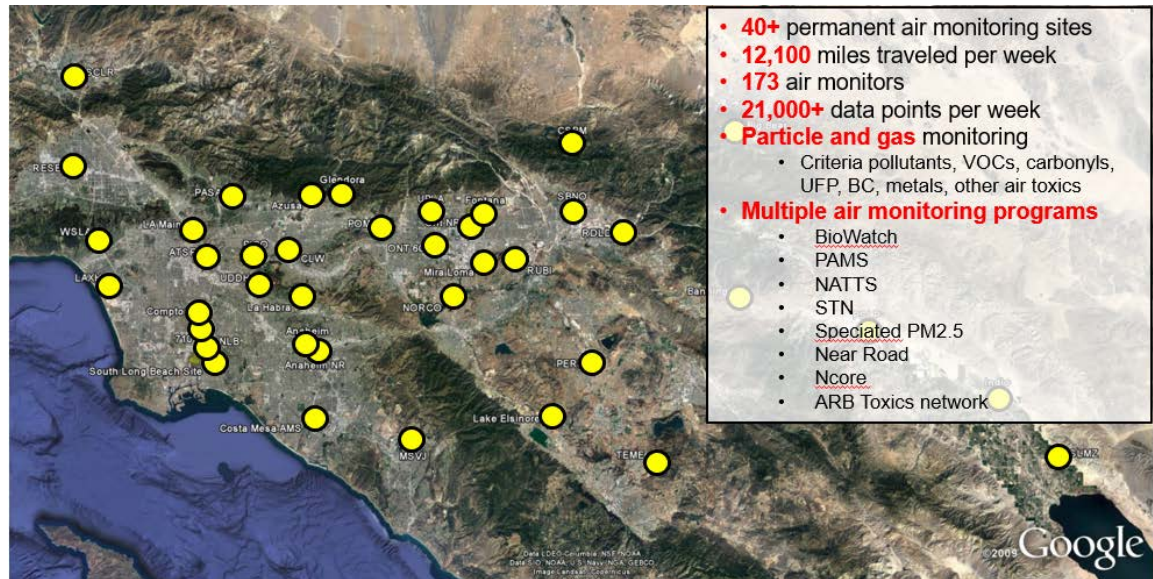
*2018 National Air Quality Conference
January 24-26, 2018; Austin, TX*

Air Quality Sensor Performance Evaluation Center (AQ-SPEC): Results from Three Years of Field and Laboratory Testing

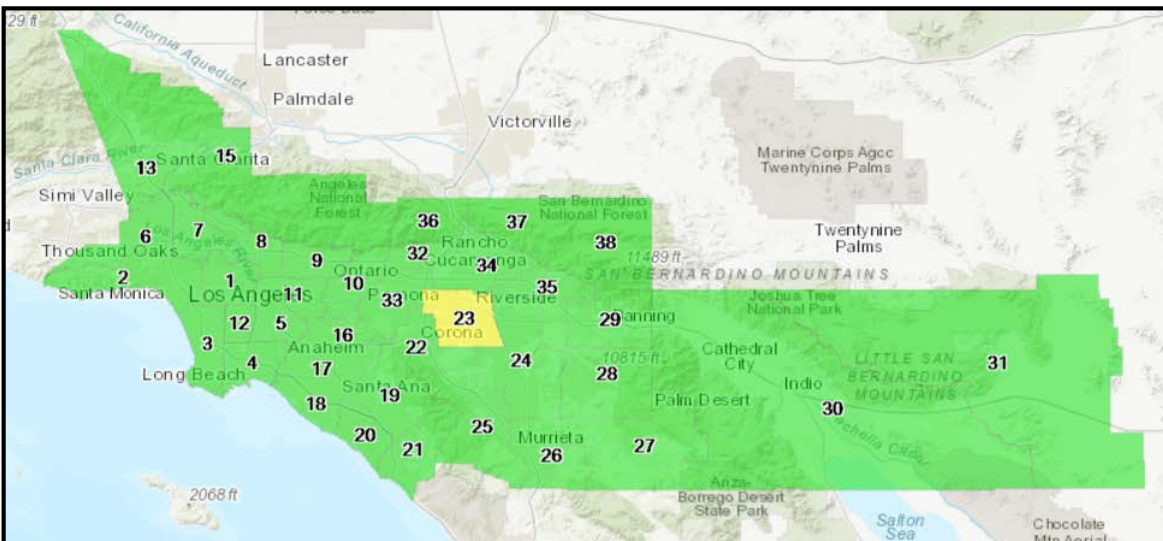
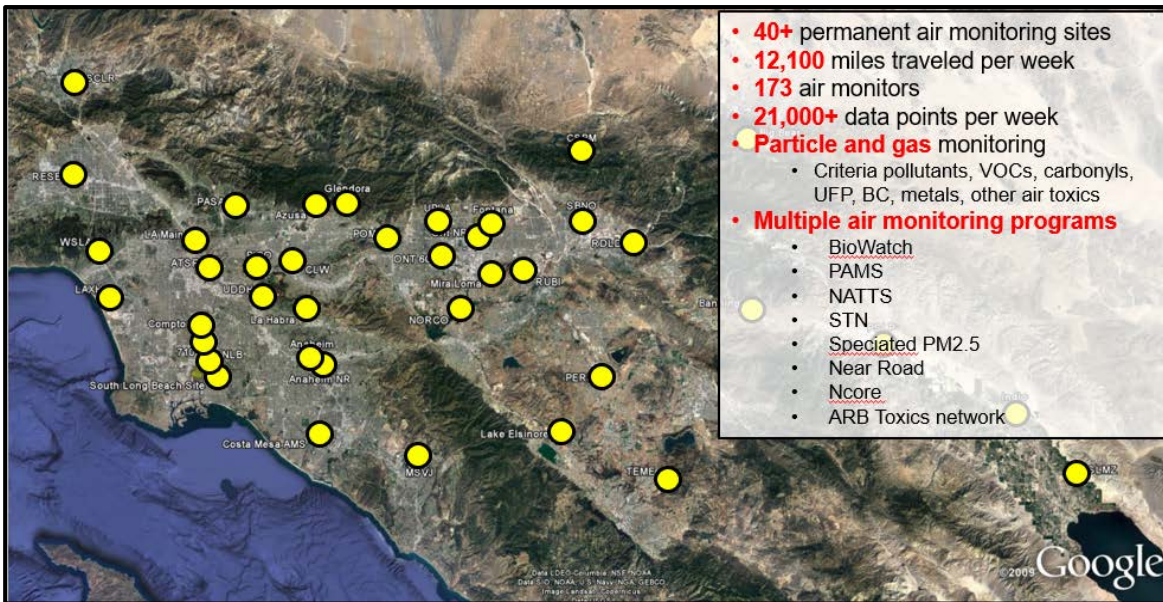
*Andrea Polidori, Ph.D.
Atmospheric Measurements Manager
South Coast Air Quality Management District
Diamond Bar, CA*

Background

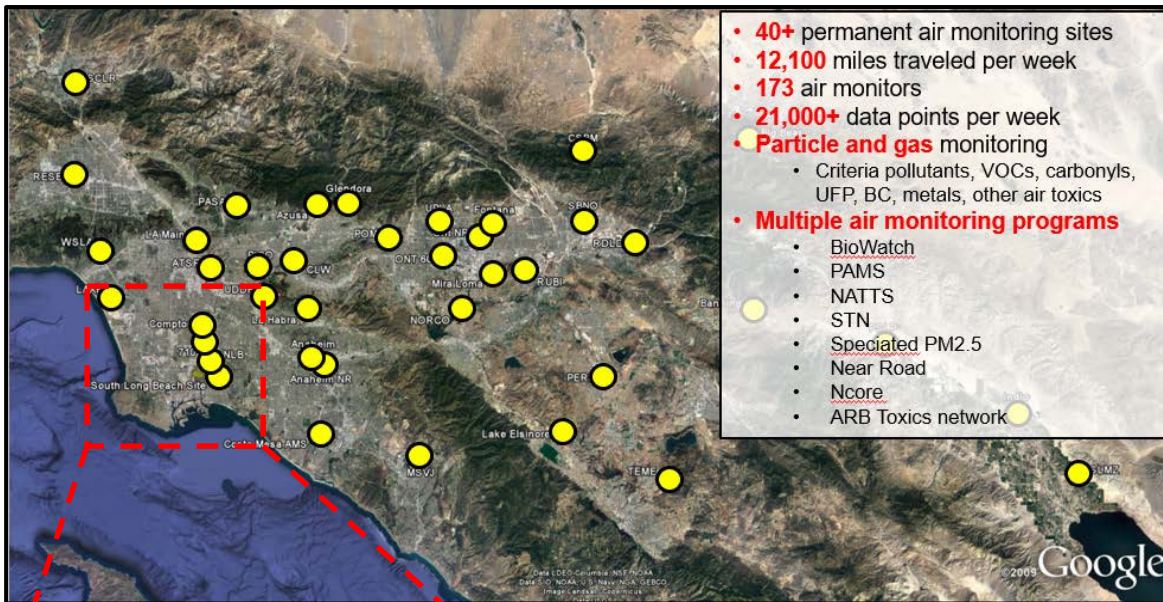
- SCAQMD is the air pollution control agency for all of Orange County and the urban portions of Los Angeles, Riverside and San Bernardino counties
- Monitoring and analysis division
 - 40+ monitoring stations (criteria pollutants and air toxics)
 - State-of-the-art laboratory



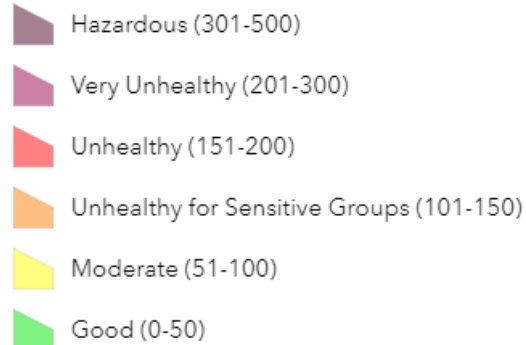
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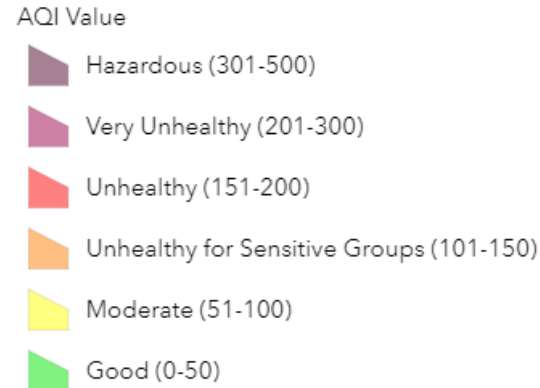
Background



AQI Value

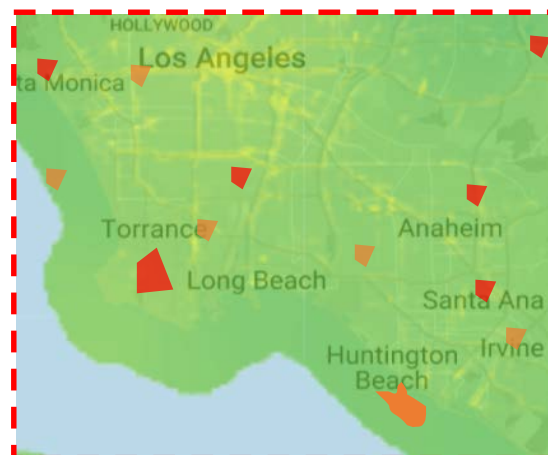


Background



➤ How would this map change if...

- ...we could monitor criteria pollutants at a lot more locations?
- ...we could include accurate air toxics info into the AQI calculation?



Used for example purposes only

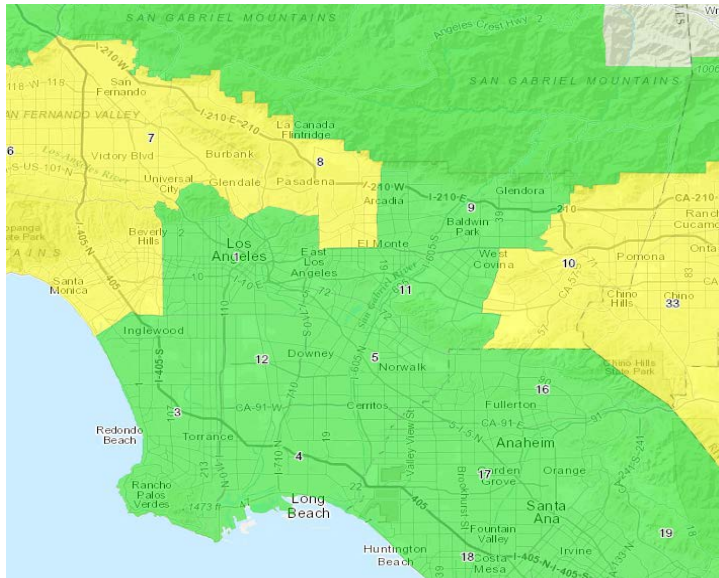
➤ Other potential sources:

- Traffic
- Refineries
- Oil wells
- Gas stations
- Marine vessels
- Ports
- Metal processing
- Power plants
- Waste disposal
- Etc.

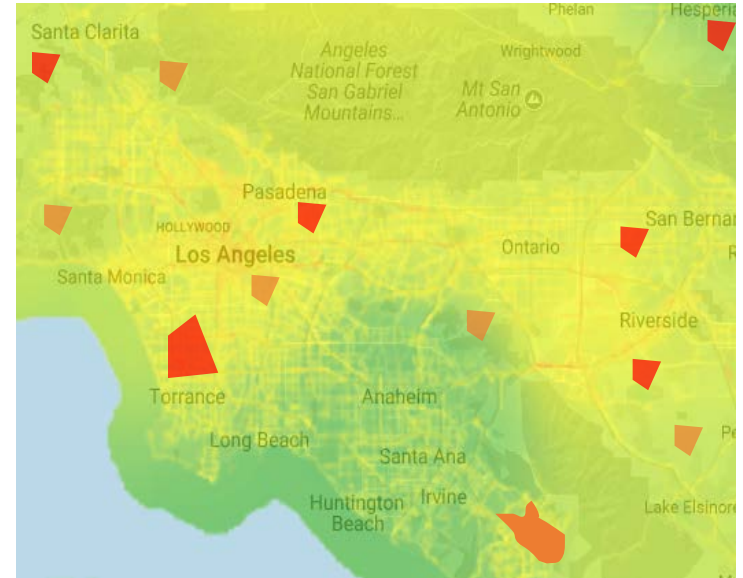
Background

➤ How do we go...

From



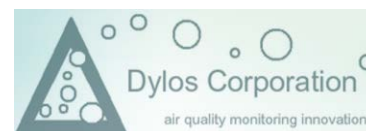
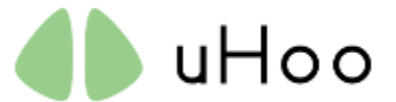
To



- Next generation monitoring (optical remote sensing, low-cost sensors, other)
- Aerial, fence-line, community, and mobile monitoring
- Satellite measurements
- Air pollution modeling
- Other

Low-Cost Air Quality Sensors

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



...and more!



AQ-SPEC

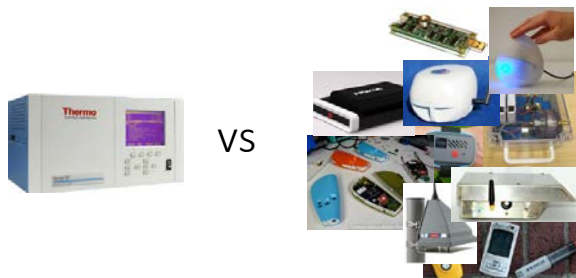
Air Quality Sensor Performance Evaluation Center

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



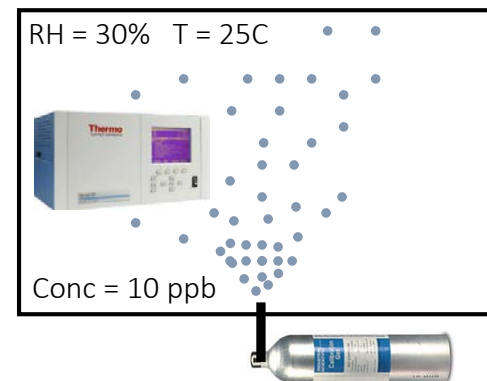
FIELD TESTING

(Side-by-side comparison w/ FRMs)



LAB TESTING

(Controlled conditions)



RESULTS

(Categorize sensors based on performance)





Field Testing

- Started in September, 2014
 - 30+ sensors evaluated
- Process
 - Sensor tested in triplicates
 - Two month deployment
 - < ~ \$2,000: purchase
 - > ~ \$2,000: lease or borrow
- Locations:
 - Rubidoux station (main)
 - Inland site
 - Fully instrumented

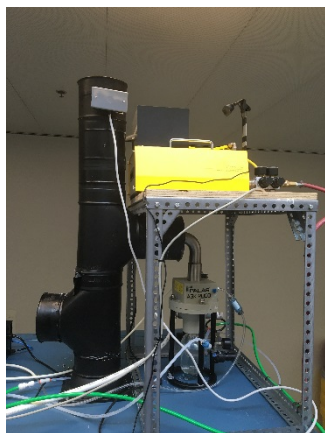




AQ-SPEC

Air Quality Sensor Performance Evaluation Center

Aerosol Test



Laboratory Testing



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, O₃, SO₂, H₂S, CH₄/NMHC



South Coast
AQMD

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South Coast Air Quality Management District

f t e r y

AQ-SPEC

Air Quality Sensor Performance Evaluation Center

g e+ f t 0



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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)
- ZB 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 (O₃), nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), hydrogen sulfide (H₂S) and methane (CH₄).
- 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?



PurpleAir



PurpleAir PA-II



RTI - MicroPEM



Shinyei - PM Evaluation Kit



Spec Sensors



TSI - AirAssure



Unitec - SENS-IT

28 products

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AQ-SPEC

Air Quality Sensor Performance Evaluation Center

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Unitec - SENS-IT

[UNITEC SENS-IT CO - Summary Report](#)
[UNITEC SENS-IT - Field Evaluation](#)
[UNITEC SENS-IT CO - Lab Evaluation](#)

General Description

The SENS-IT (TF-MOS: Thick Film Metal Oxide Semiconductor) measures CO (carbon Monoxide) (0.1-80 ppm), NO₂ (nitrogen dioxide) (10-250 ppb), O₃ (ozone) (10-250 ppb), C₆H₆ (benzene) (0.1-30 ppb) and CH₄ (methane) (1-1,500 ppm).

Principle of Operation

The active surface of the sensor is based on a specific nano-structured semiconductor metal oxide. The first reaction which happens on the surface of the sensor is the adsorption of atmospheric oxygen with consequent charge transfer from semiconductor to oxygen molecules. The second reaction is related to specific gas to monitor, which while reacts with adsorbed oxygen (through Red-Ox reactions) allows the electrons to be released in the conduction band of the semiconductor. Taking the current signals from the sensors during these reactions, the direct concentration of the specific gas can be measured. Selectivity and sensitivity are reached using special doped semiconductor metal oxides.

Features

- Dimensions: 50 x 50 x 90 (H) mm
- Weight: 200 g
- Battery: No
- Power supply: Yes (+12 V DC)
- Power consumption: 3.0 - 4.0 W
- Sensor lifetime: N/A
- Clock function: No (No internal clock, must be connected to computer for time/date stamp)
- Sampling mechanism: Fan
- Environmental operating conditions: N/A
- PC data logging: Yes (USB to RS485 cable)
- Signal Output: Linear 0-5 V / Digital RS485
- Weatherproof: No

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 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 PM _{2.5} : R ² ~ 0.38 to 0.80 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		
	Mojji China (Aimut)	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 PM _{2.5} : R ² ~ 0.2		
	Origins (Laser Egg)	Optical	PM _{2.5} & PM ₁₀	~\$200	PM _{2.5} : R ² ~ 0.58 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 PM _{2.5} : R ² ~ 0.77 to 0.92 PM ₁₀ : R ² ~ 0.32 to 0.44	PM _{1.0} : R ² ~ 0.95 PM _{2.5} : R ² ~ 0.99 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 PM _{2.5} : R ² ~ 0.93 to 0.97 PM ₁₀ : R ² ~ 0.66 to 0.70	PM _{1.0} : R ² ~ 0.99 PM _{2.5} : R ² ~ 0.99 PM ₁₀ : R ² ~ 0.95	PDF (1,328 KB)
	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

Most PM sensors showed:




- Minimal down time
- Moderate intra-model variability
- Strong correlation (R²) with EPA “approved” instruments (e.g., FEM)

However...

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

Gaseous Sensors

Results

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	R ² ~ 0.99	PDF (1,197 KB)
	Air Quality Egg (Version 1)	Metal Oxide	CO, NO ₂ & O ₃	~\$200	CO: R ² ~ 0.0 NO ₂ : R ² ~ 0.40 O ₃ : R ² ~ 0.85		
	Air Quality Egg (Version 2)	Electrochem	CO & NO ₂	~\$240	CO: R ² ~ 0.0 NO ₂ : R ² ~ 0.0		
	Air Quality Egg (Version 2)	Electrochem	O ₃ & SO ₂	~\$240	O ₃ : R ² ~ 0.0 to 0.20 SO ₂ : R ² n/a		
	AQMesh (v.4.0) (Discontinued)	Electrochem	CO, NO, NO ₂ & O ₃	~\$10,000	CO: R ² ~ 0.42 to 0.80 NO: R ² ~ 0.0 to 0.44 NO ₂ : R ² ~ 0.0 to 0.46 O ₃ : R ² ~ 0.46 to 0.83		
	Perkin Elmer (ELM)	Metal Oxide	NO, NO ₂ & O ₃	~\$5,200	NO: R ² n/a NO ₂ : R ² ~ 0.0 O ₃ : R ² ~ 0.89 to 0.96		
	Smart Citizen Kit	Metal Oxide	CO, NO ₂	~\$200	CO: R ² ~ 0.50 to 0.85 NO ₂ : R ² ~0.0		
	Spec Sensors	Electrochem	CO, NO ₂ & O ₃	~\$500	CO: R ² ~ 0.84 to 0.90 NO ₂ : R ² ~ 0.0 to 0.16 O ₃ : R ² ~ 0.0 to 0.24		
	UNITEC (SENS-IT)	Metal Oxide	CO, NO ₂ & O ₃	~\$2,200	CO: R ² ~ 0.33 to 0.43 NO ₂ : R ² ~ 0.60 to 0.65 O ₃ : R ² ~ 0.72 to 0.83	CO: R ² ~ 0.99 O ₃ : R ² ~ 0.82 to 0.90	CO: PDF (1,283 KB) O ₃ : PDF (1,177 KB)

Most gaseous sensors showed:

- Acceptable data recovery
- Wide intra-model variability range
- CO; NO; O₃ (when measured alone): good correlation with FRMs
- O₃ + NO₂: low correlation with FRM (potential O₃/NO₂ interference)
- SO₂; H₂S; VOC: difficult to measure with available sensors

AQ-SPEC - What's Next?

Sensor 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?
 - Regulatory?
 - Fenceline?
 - Improve network design?
 - Permitting?
 - Other?



.....for what?

- Very expensive to implement correctly
 - Multiple field testing locations across the Nation
 - Multiple laboratory testing facilities
 - Extended testing time

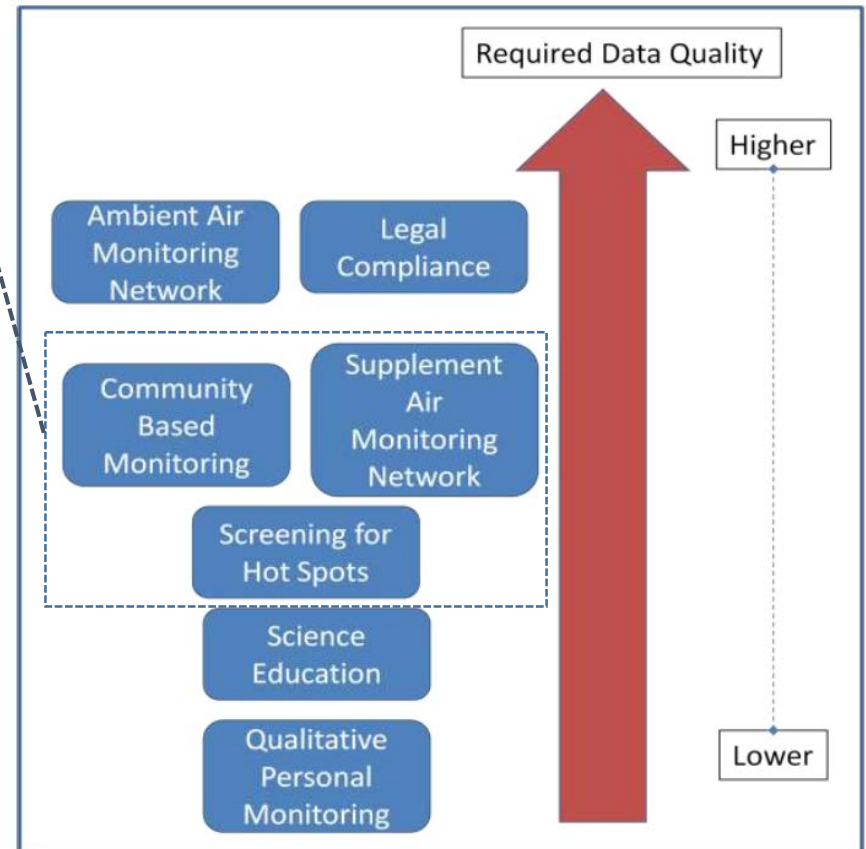


Sensor Applications

- 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.

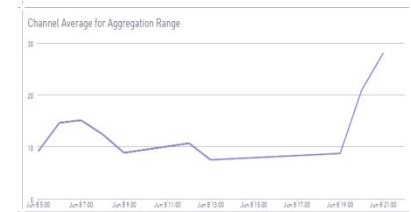


EPA's "DRAFT Roadmap for Next Generation Air Monitoring"

Low-cost Sensors / High-cost Networks

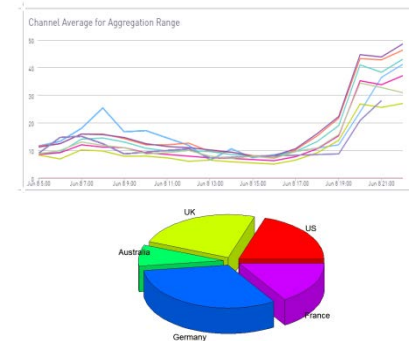
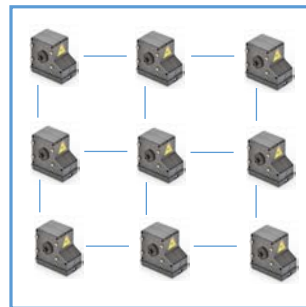
➤ Single user (e.g. 1 sensor)

- Cost: \$
 - Hardware
 - Minimal maintenance



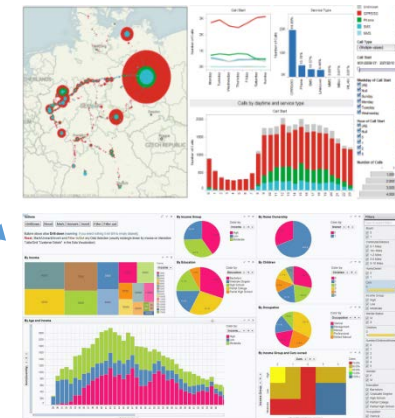
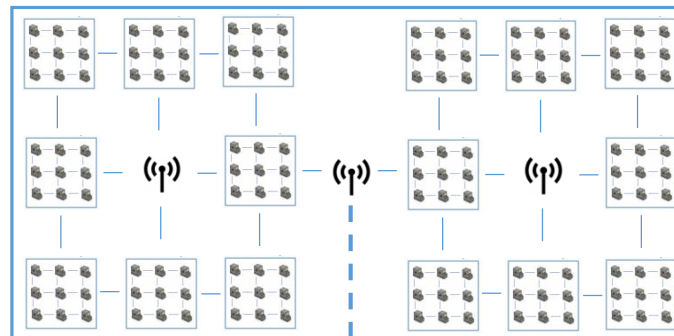
➤ Small sensor network (e.g. 9 sensors)

- 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



AQ-SPEC – Current Activities

Fenceline Monitoring: Waste Disposal Facility



- Monitor fugitive emissions from a Waste Disposal facility in Southern California
- 9 sensor nodes deployed at facility fenceline on June 2016
- Wireless network / remote server
- Real-time PM_{10} , $PM_{2.5}$ and PM_{1} monitoring

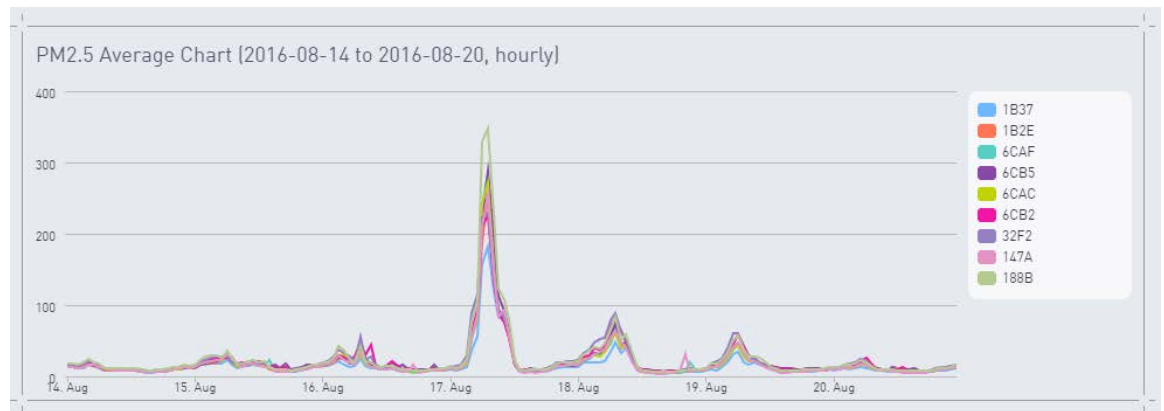


AQ-SPEC – Current Activities

Fenceline Monitoring: Waste Disposal Facility



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



AQ-SPEC – Current Activities

Fenceline Monitoring: Refinery

(EPA Community Scale 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)



AQ-SPEC – Current Activities

Fenceline Monitoring: Refinery

(EPA Community Scale Grant)

- Mobile ORS: *quarterly surveys of emission measurements and concentrations mapping*
- “Low-cost” sensors network: *long-term monitoring of VOC and PM_{2.5} at facility fenceline and inside communities*



AQ-SPEC – Current Activities

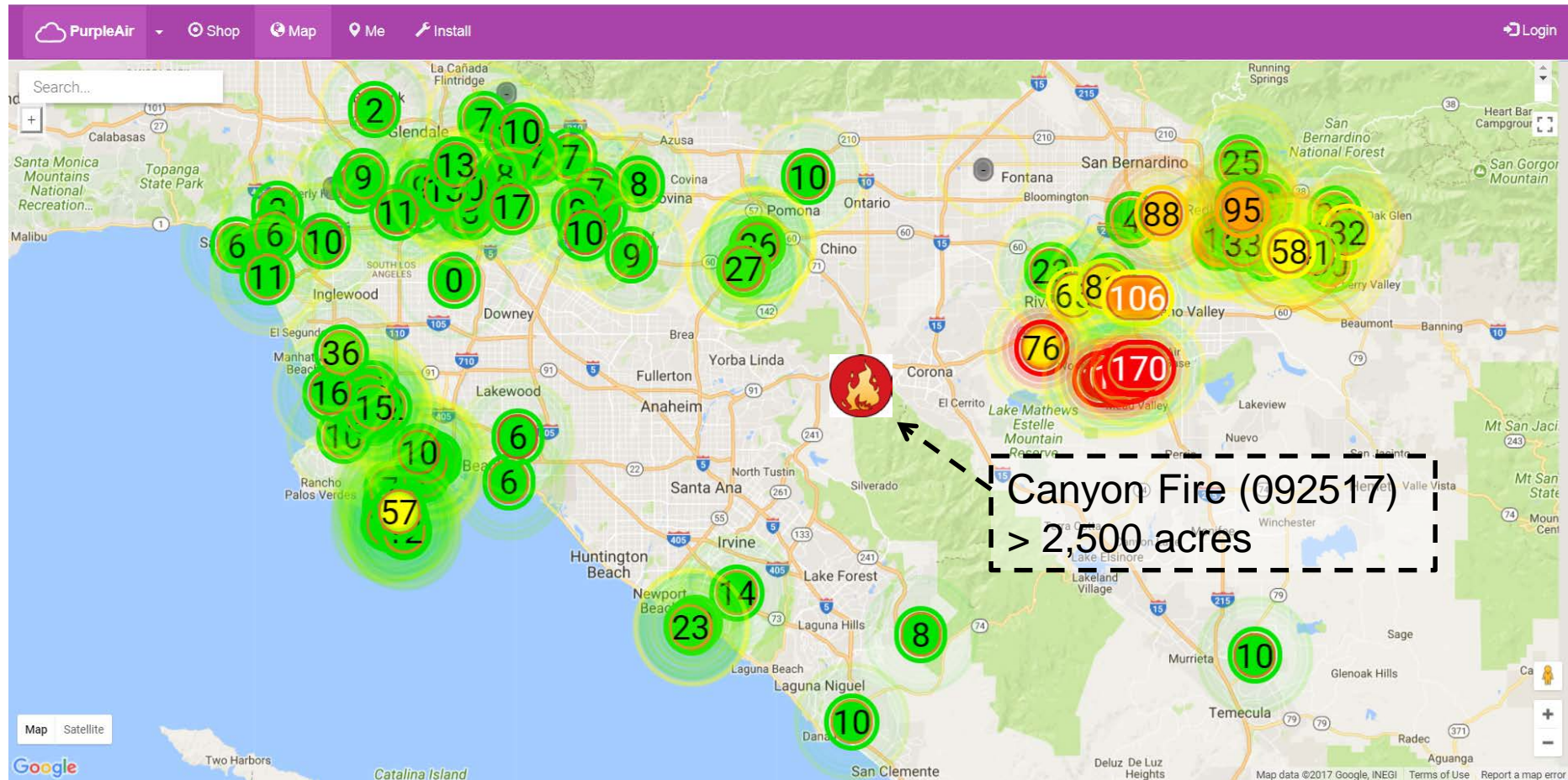
Fenceline Monitoring: Refinery

(EPA Community Scale Grant)



AQ-SPEC – Current Activities

PM Sensor Network



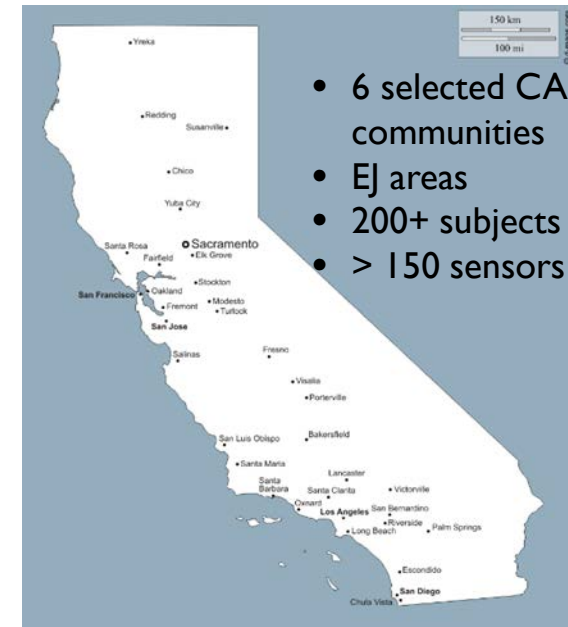
Note: Values are reported as AQI units

AQ-SPEC – Current Activities

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

Engage, educate, and empower California communities on the use and applications of “low-cost” air monitoring sensors

- Provide communities with the knowledge necessary to select, use and maintain low-cost sensors and to correctly interpret the collected data
- Three year study:
 - SCAQMD (PI)
 - University of California Los Angeles (UCLA; Co-PI)
 - Sonoma Technology Inc. (STI; Co-PI)
 - BAAQMD
 - Santa Barbara County APCD
 - Other CAPCOA agencies
 - Community Groups
 - Leisure World (Seal Beach, CA)
 - Weather Underground
 - University of Auckland (New Zealand)



AQ-SPEC – Current Activities

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

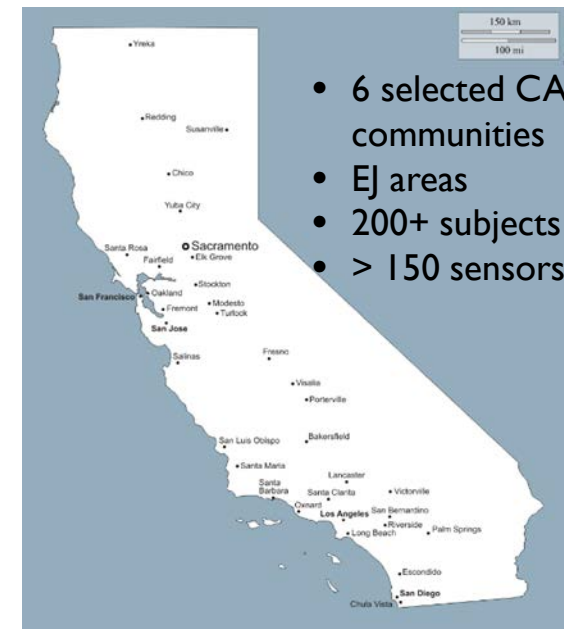
Engage, educate, and empower California communities on the use and applications of “low-cost” air monitoring sensors

➤ Four specific aims:

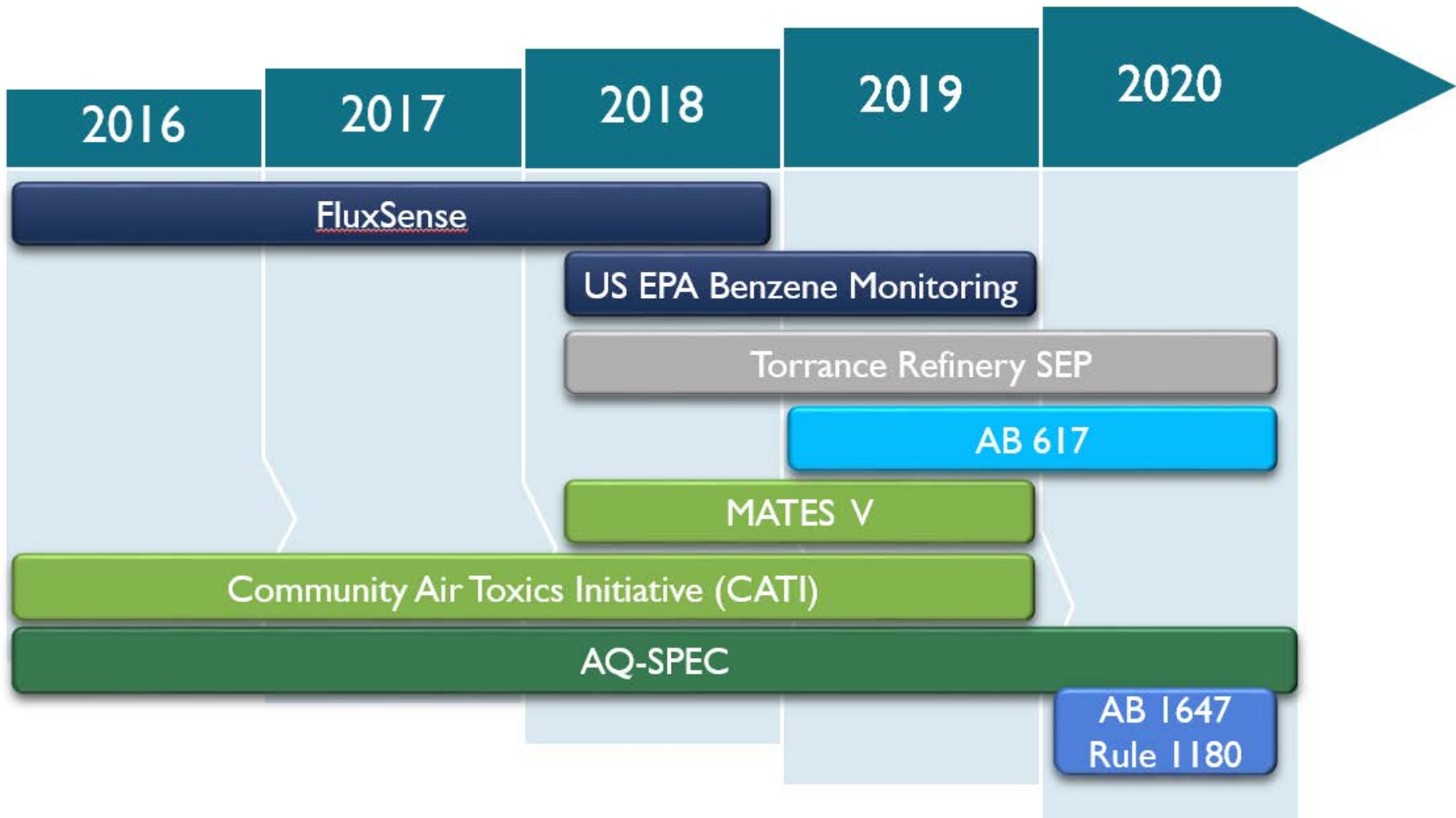
1. Develop educational material for communities
2. Evaluate / identify candidate sensors for deployment
3. Deploy selected sensors in California communities
4. Communicate the lessons learned to the public

➤ On-going activities:

- Wide Spread Sensor Deployment across California
 - ~450 PM sensors
 - 100 Aeroqual nodes (i.e., PM, O₃, NO_x)
- Cloud Based Platform Development
 - Data ingestion and storage
 - Data visualization and mapping
 - Data dissemination



Current and Upcoming Air Toxic Initiatives



Thanks!

The AQ-SPEC Team

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