South Coast AQMD

“Making Sense of Sensors” Conference
Diamond Bar; September 27, 2017

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

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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
  - Community monitoring
- Need to systematically evaluate their performance
  - Accuracy, precision, durability and overall reliability
  - Calibration and drift
  - Other performance issues

uHoo

Clarity

aeroqual

axetris

PurpleAir

AQMesh

habitat map

foobot

SPEC SENSORS

TSI

Dylos Corporation air quality monitoring innovation

…and more!

AQ-SPEC

Air Quality Sensor Performance Evaluation Center

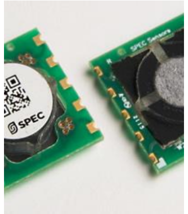
- Established in July 2014
- Over $600,000 investment
- Main Goals & Objectives
  - Provide guidance & clarity
  - Promote successful evolution and use of sensor technology
  - Minimize confusion
- Sensor Selection Criteria
  - Commercially available
    - *Optical*
    - *Electrochemical*
    - *Metal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









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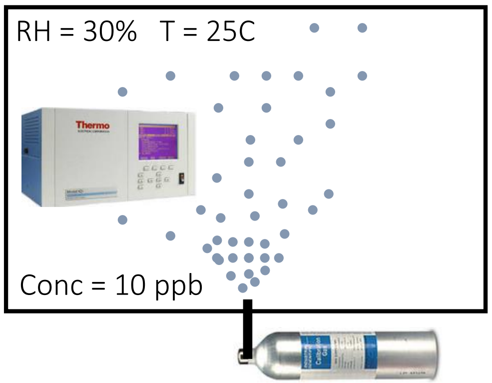
FIELD TESTING
(Side-by-side comparison w/ FRMs)

VS

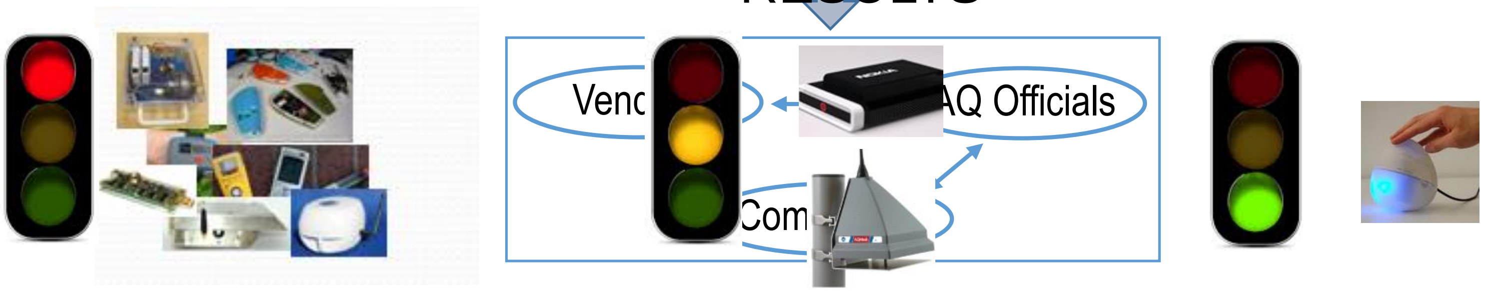
LAB TESTING
(Controlled conditions)



RESULTS
(Categorize sensors based on performance)

SCAQMD
Website / Clearinghouse

RESULTS



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Field Testing

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

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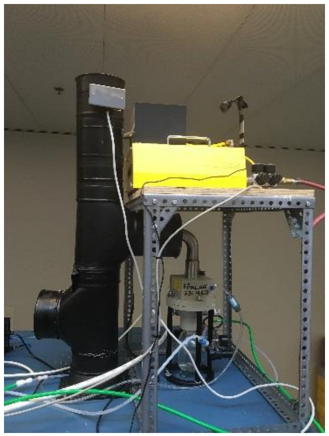
Laboratory Testing

Aerosol Test



Gas Test

Laboratory Testing (cont.)

<u>T and RH controlled</u>: T (0-50 ^{0}C); RH (5-95%)

<u>Particle testing</u>

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

<u>Gas testing</u>

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

www.aqmd.gov/aq-spec

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Air Quality Sensor Performance Evaluation Center

AQ-SPEC

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?

www.aqmd.gov/aq-spec

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AQ-SPEC

Air Quality Sensor Performance Evaluation Center

Back to Sensors Page

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), NO_2 (nitrogen dioxide) (10-250 ppb), O_3 (ozone) (10-250 ppb), C_6H_6 (benzene) (0.1-30 ppb) and CH_4 (methane) (1-1,500 ppm).

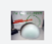
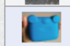
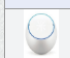
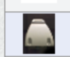
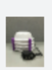
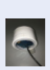
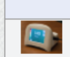
Principle of Operation

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	$PM_{(0.5\text{-}2.5)}$	~$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 $PM_{2.5}$: 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

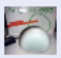
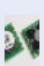
Most PM sensors showed:

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

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)

Results

<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

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?



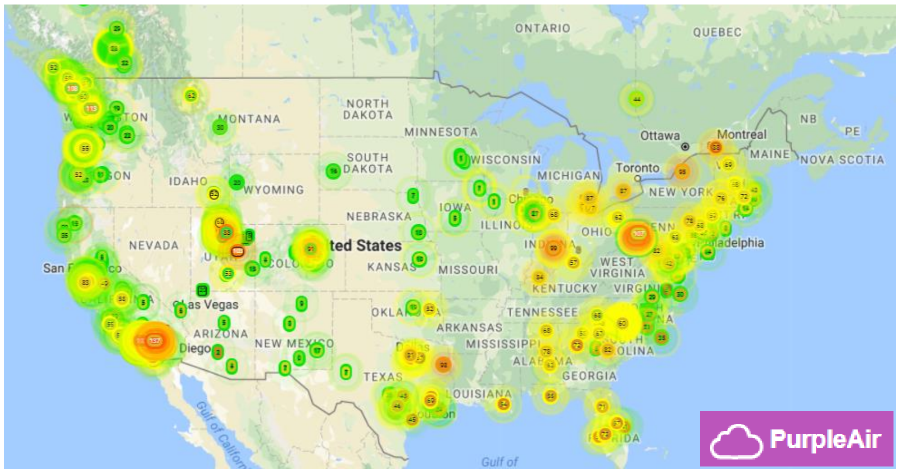
- "Certified" for which use?
  - Regulatory?
  - Fenceline?
  - Improve network design?
  - Permitting?
  - Other?

…….for what?

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

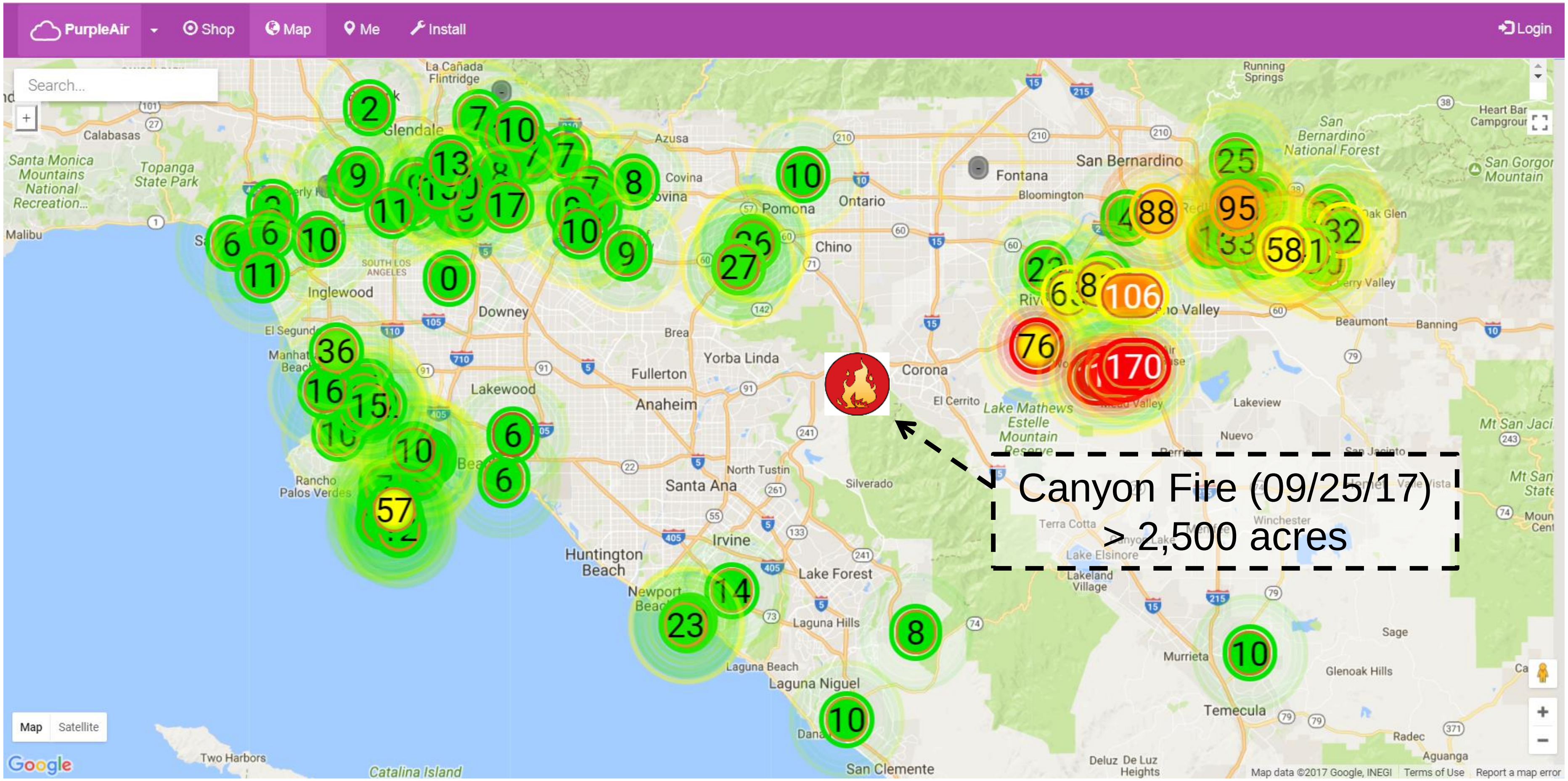
AQ-SPEC – Current Activities
PM Sensor Network

PurpleAir PM sensor network (US only)



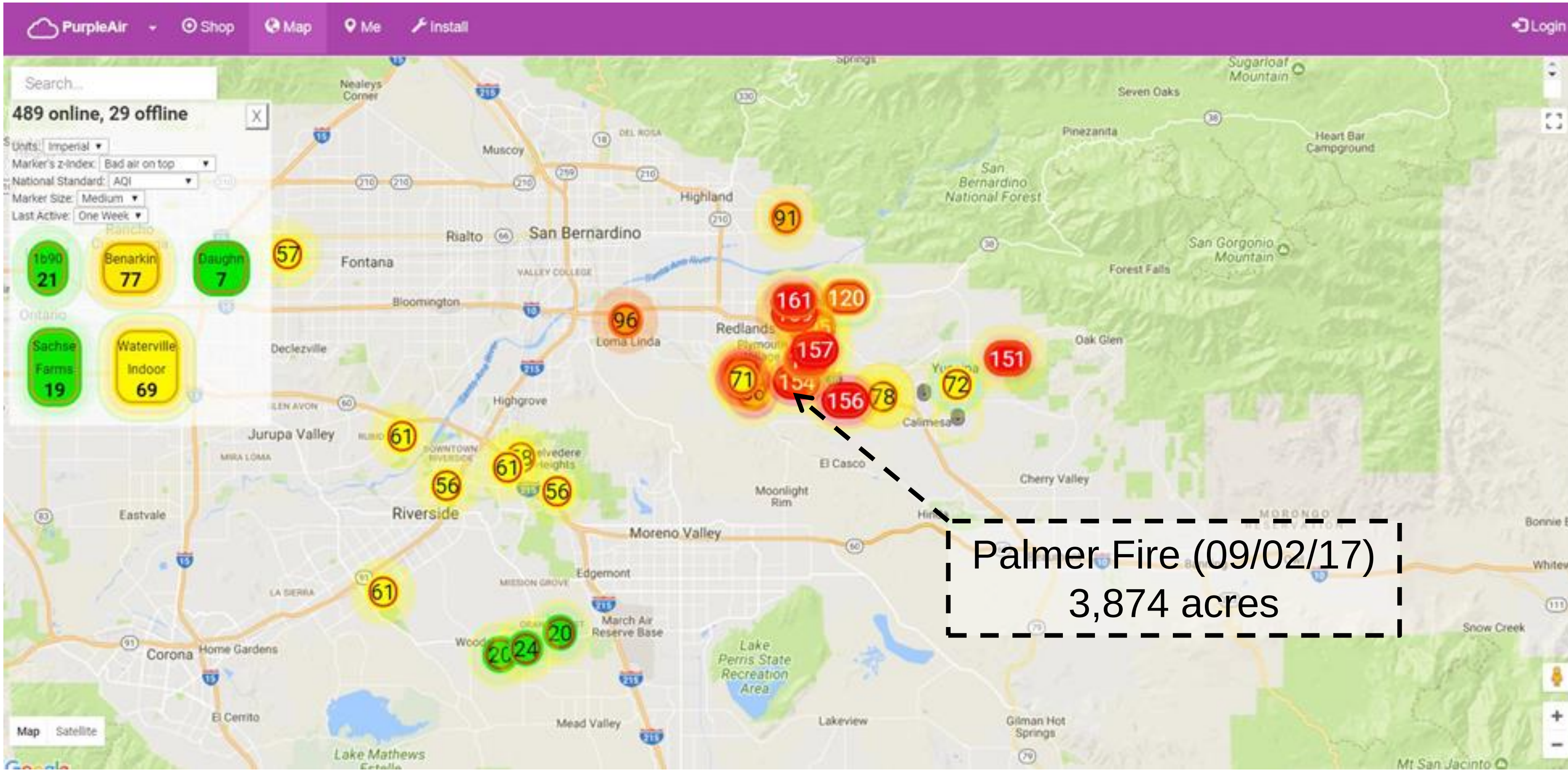
- Over 60 “low-cost” PM sensors deployed by AQ-SPEC in SoCal
- Real-time PM_1, $PM_{2.5}$ and PM_{10} monitoring
- Wireless network / remote server
  - *Sensor device/data management: Microsoft Azure IoT + Power Bi*
- Project goals
  - *Test sensor durability*
  - *Show ability to scale up*
  - *Help improve accuracy of satellite data*
  - *Study spatial/temporal PM variability*
  - *Provide monitoring during wildfires*

AQ-SPEC – Current Activities
PM Sensor Network (Wildfire Event)



Note: Values are reported as AQI units

AQ-SPEC – Current Activities
PM Sensor Network (Wildfire Event)



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)

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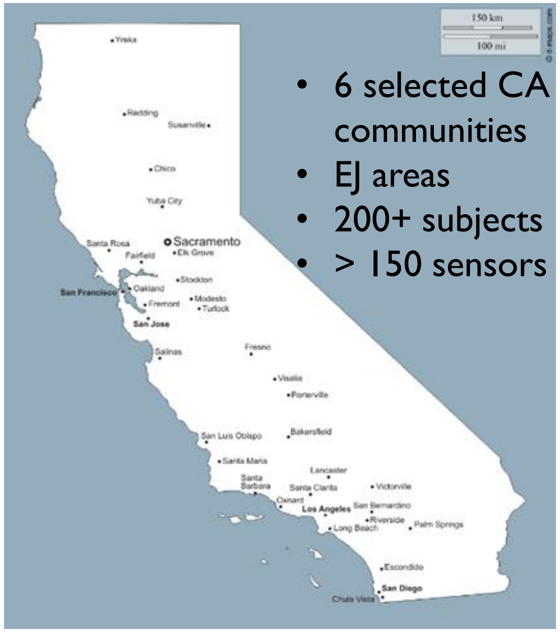
STi Sonoma Technology, Inc.



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:
  - Wide Spread Sensor Deployment across California
    - 430 PM sensors
    - 100 Aeroqual nodes (i.e., PM, O_3, NOx)
  - Cloud Based Platform Development
    - Data ingestion and storage
    - Data visualization and mapping
    - Data dissemination

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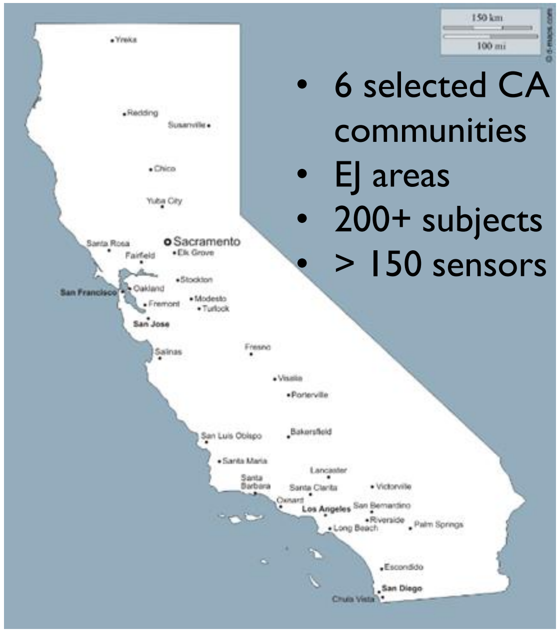
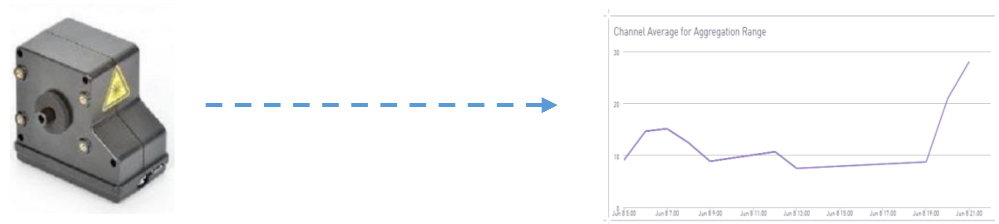
STi Sonoma Technology, Inc.



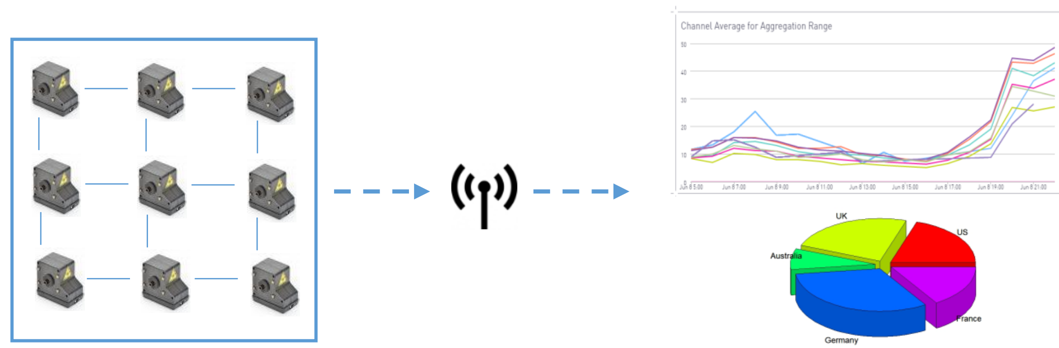
- 6 selected CA communities
- EJ areas
- 200+ subjects
- > 150 sensors

Low-cost Sensors / High-cost Networks

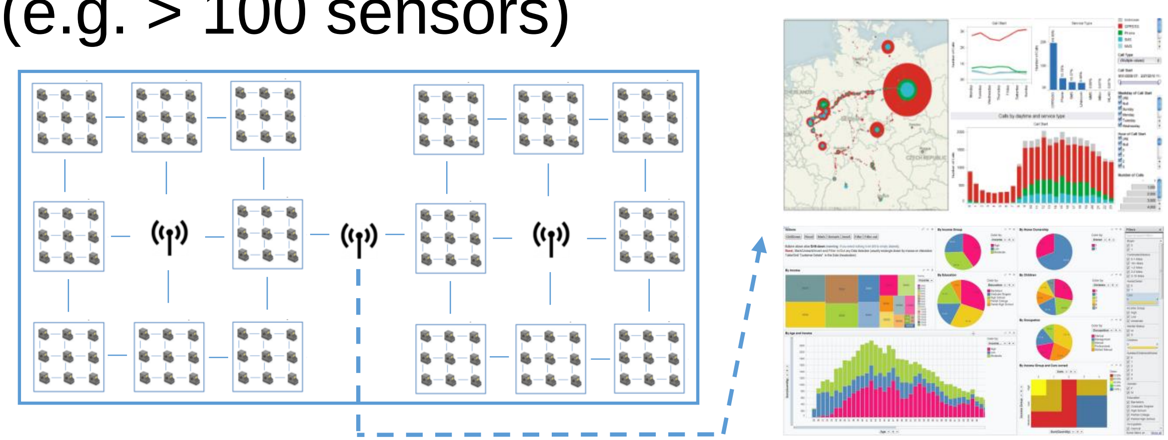
- Single user (e.g. 1 sensor)
  - Cost: $
    - Hardware
    - Minimal maintenance



- 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



Thanks!

The AQ-SPEC Team

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