AAAR CIARA

AQ-SPEC
Air Quality Sensor Performance Evaluation Center

10th International Aerosol Conference - Tutorial

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

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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

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

uHoo
Clarity
aeroqual
axetris
PurpleAir
AQMesh
habitat map
foobot
TSI
SPEC SENSORS
Dylos Corporation
air quality monitoring innovation

...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



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Air Quality Sensor Performance Evaluation Center

- 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…?

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2014 – 2018: Over 30 PM sensors evaluated

- 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

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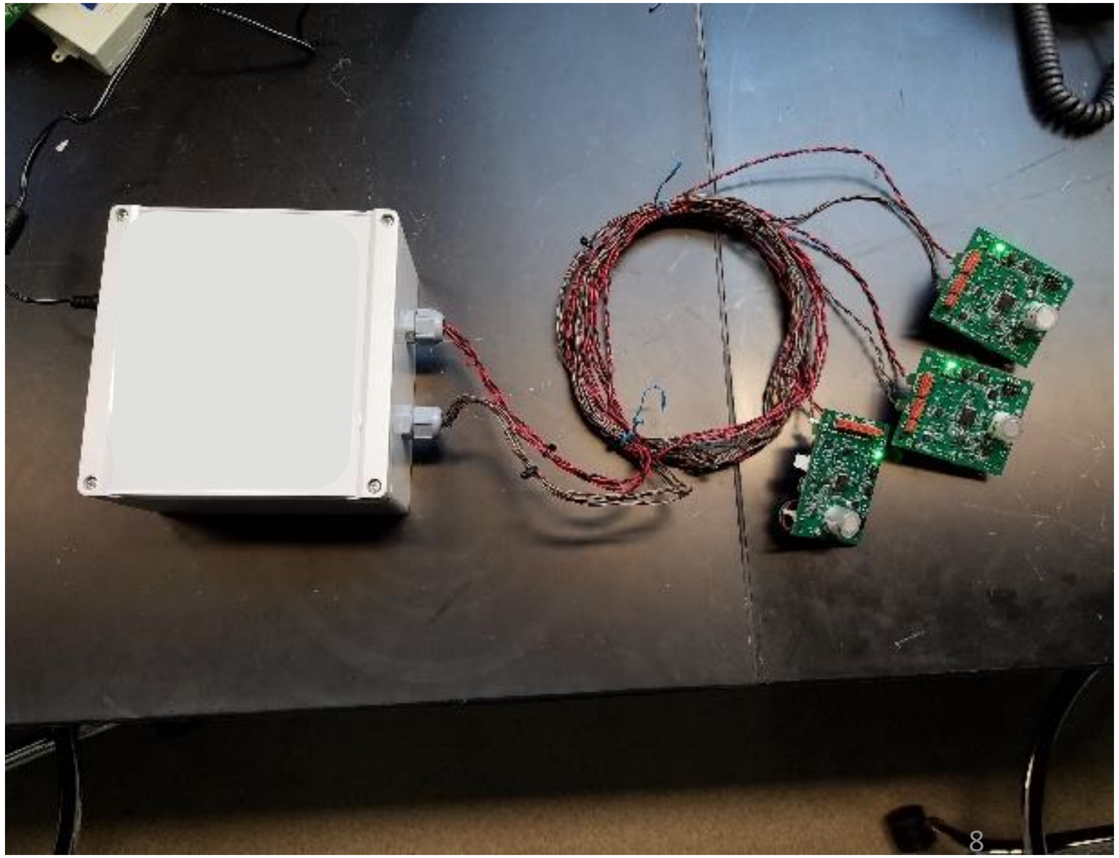
Field Testing

- 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



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PM Sensors

Sensor Image	Manufacturer (Model)	Type	Pollutant(s)	Approx. Cost (USD)	*Field R^2	*Lab R^2	Summary Report
	Aeroqual (AQY v0.5)	Optical	$PM_{2.5}$	~$3,000 (multi-sensor)	R^2 ~ 0.84 to 0.87		
	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)
	Cair	Optical	PM(1-2um), PM(3-10um)	~$200	$PM_{2.5}$: R^2 ~ 0.43 to 0.51 PM_{10}: R^2 ~ 0.39 to 0.51		
	Clarity (Node)	Optical	$PM_{2.5}$	~$1300	R^2 ~ 0.73 to 0.76		
	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		
	IQAir (AirVisual Pro)	Optical	$PM_{2.5}$, PM_{10}	~$270	$PM_{2.5}$: R^2 ~ 0.69 to 0.73 PM_{10}: R^2 ~ 0.24 to 0.41	$PM_{2.5}$: R^2 ~ 0.99	PDF (1,461 KB)
	Met One (E-Sampler)	Optical	$PM_{1.0}$, $PM_{2.5}$, PM_{10}, TSP	~$5,500	$PM_{2.5}$: R^2 ~ 0.55 to 0.62		
	Met One (Neighborhood Monitor)	Optical	$PM_{2.5}$	~$1,900	R^2 ~ 0.53 to 0.67		

Results

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

PM Sensors

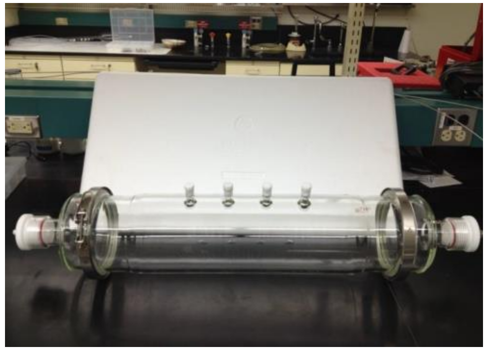
Sensor Image	Manufacturer (Model)	Type	Pollutant(s)	Approx. Cost (USD)	*Field R^2	*Lab R^2	Summary Report
	Moji China (Airnut)	Optical	$PM_{2.5}$	~$150	R^2 ~ 0.81 to 0.88		
	Naneos (Partector)	Electrical	PM (LDSA: Lung-Deposited Surface Area)	~$7,000	$PM_{1.0}$: R^2 ~ 0.1 $PM_{2.5}$: R^2 ~ 0.2		
	Origins (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-I-Indoor)	Optical	$PM_{1.0}$, $PM_{2.5}$ & PM_{10}	~$180	$PM_{2.5}$: R^2 ~ 0.75 PM_{10}: R^2 ~ 0.36 to 0.46		
	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)
	SainSmart (Pure Morning P3)	Optical	$PM_{2.5}$	~$170	R^2 ~ 0.73	R^2 ~ 0.99	PDF (1,186 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	R^2 ~ 0.99	PDF (5,647 KB)
	uHoo	Optical	$PM_{2.5}$	~$300	R^2 ~ 0.0		

Polidori A, Feenstra B, Papapostolou V, Zhang H. 2017. AQ-SPEC Field Evaluation of Low-cost Air Quality Sensors - Field Setup and Testing Protocol (Diamond Bar, CA)

Previous Chamber Work

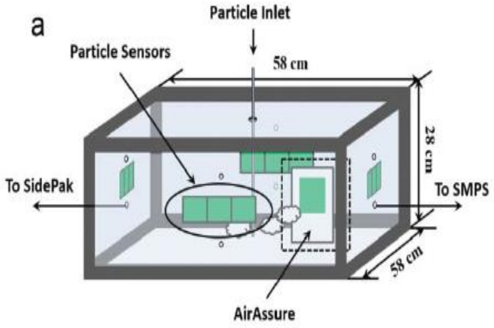
Spinelle et al., 2013
Institute for Environment and Sustainability
Joint Research Centre, European Commission

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

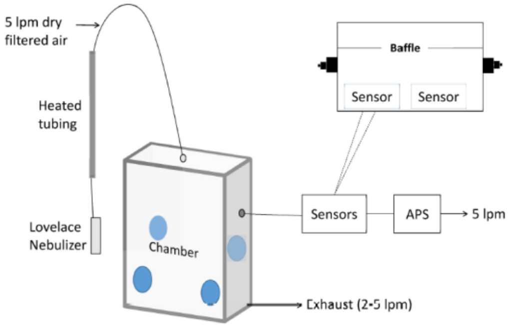


Wang et al., 2015, Aerosol Sci Tech

Washington University in St.Louis



Austin et al., 2015, PLOS One
University of Washington



South Coast AQMD – Laboratory

25,000 ft^2

- **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
- **Cr^{6+}** by ICP-MS
- **TGA**, **pH** and **vapor pressure**
- **TCA**, **CO**, **CH_4**, **CO_2**
- **Compliance**:
  Paints, coatings, petroleum products, adhesives, lubricants and stack samples for VOC, inorganic components (e.g., metals, acids, SOx and NOx)

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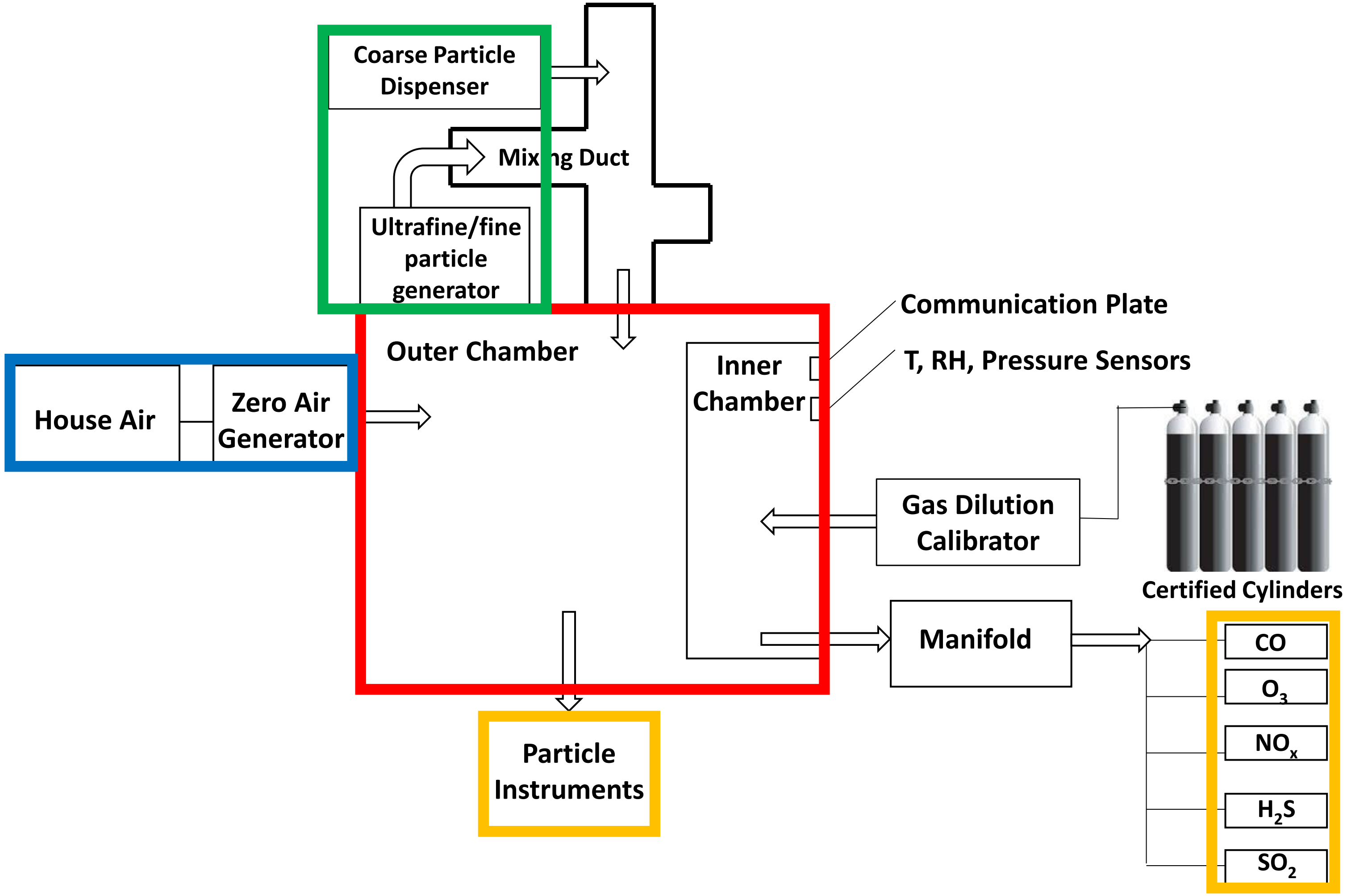
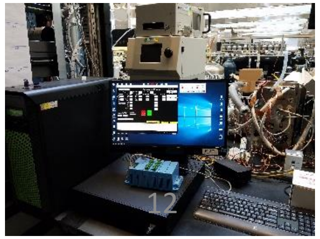


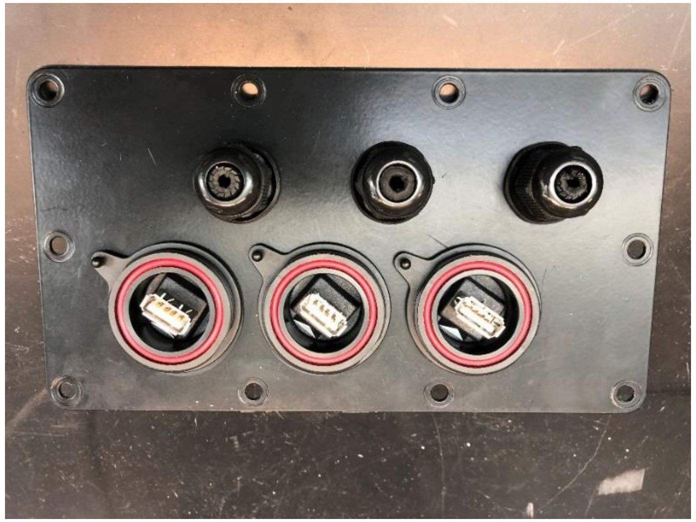
1. Chamber system (sophisticated HVAC)
2. “Zero air” generation system
3. Two Particle systems
4. FEM/FRM/BAT reference instruments
5. Integrated software

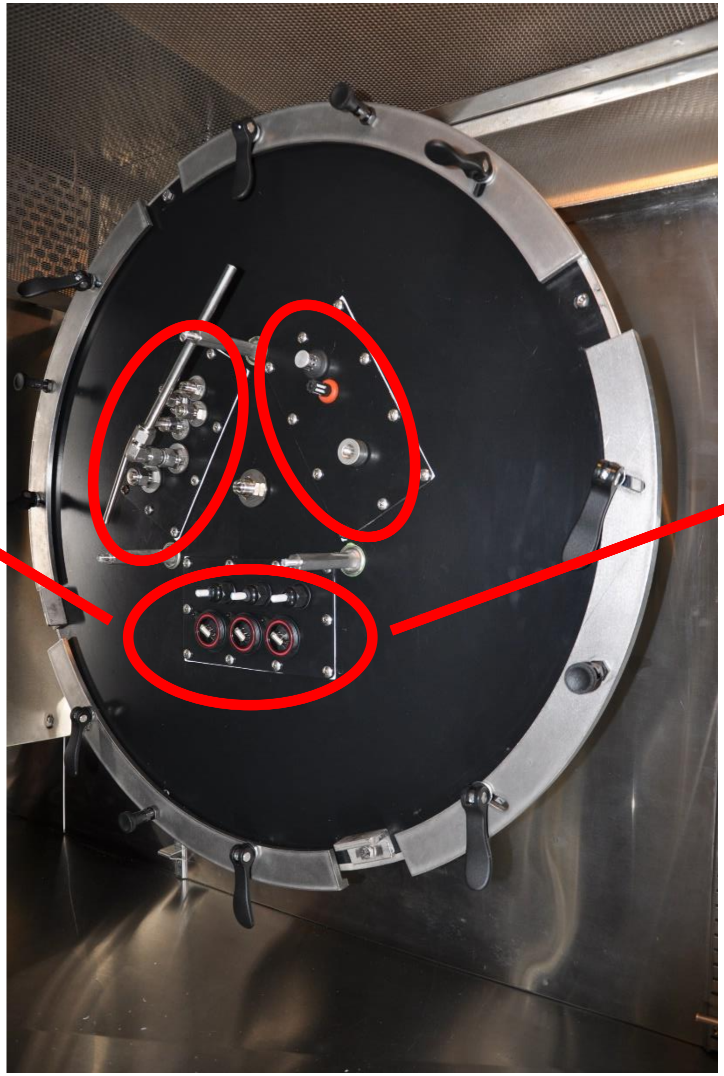


- ✓ Outer chamber
- ✓ Made of stainless steel
- ✓ Shape: Rectangular
- ✓ Volume: 1.3 m^3
- ✓ HVAC system
- ✓ Louvered ceiling surface
- ✓ Set of two fans

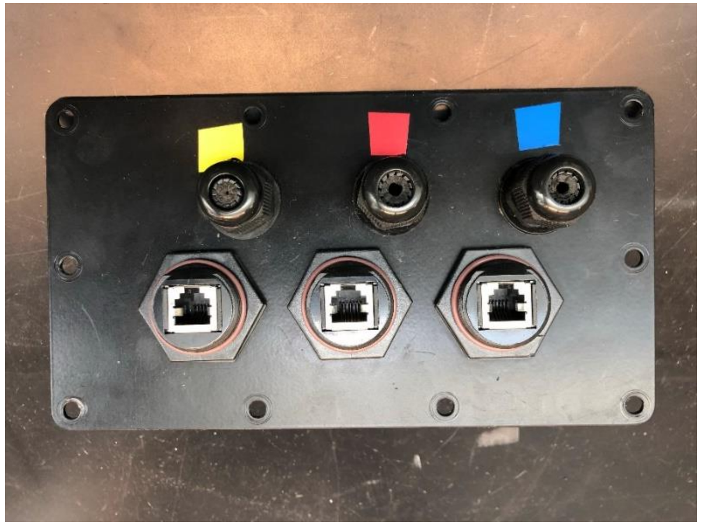
- ✓ Inner chamber
- ✓ Teflon-coated Stainless Steel
- ✓ Shape: Cylindrical
- ✓ Volume: 0.11 m^3

Ethernet & power ports



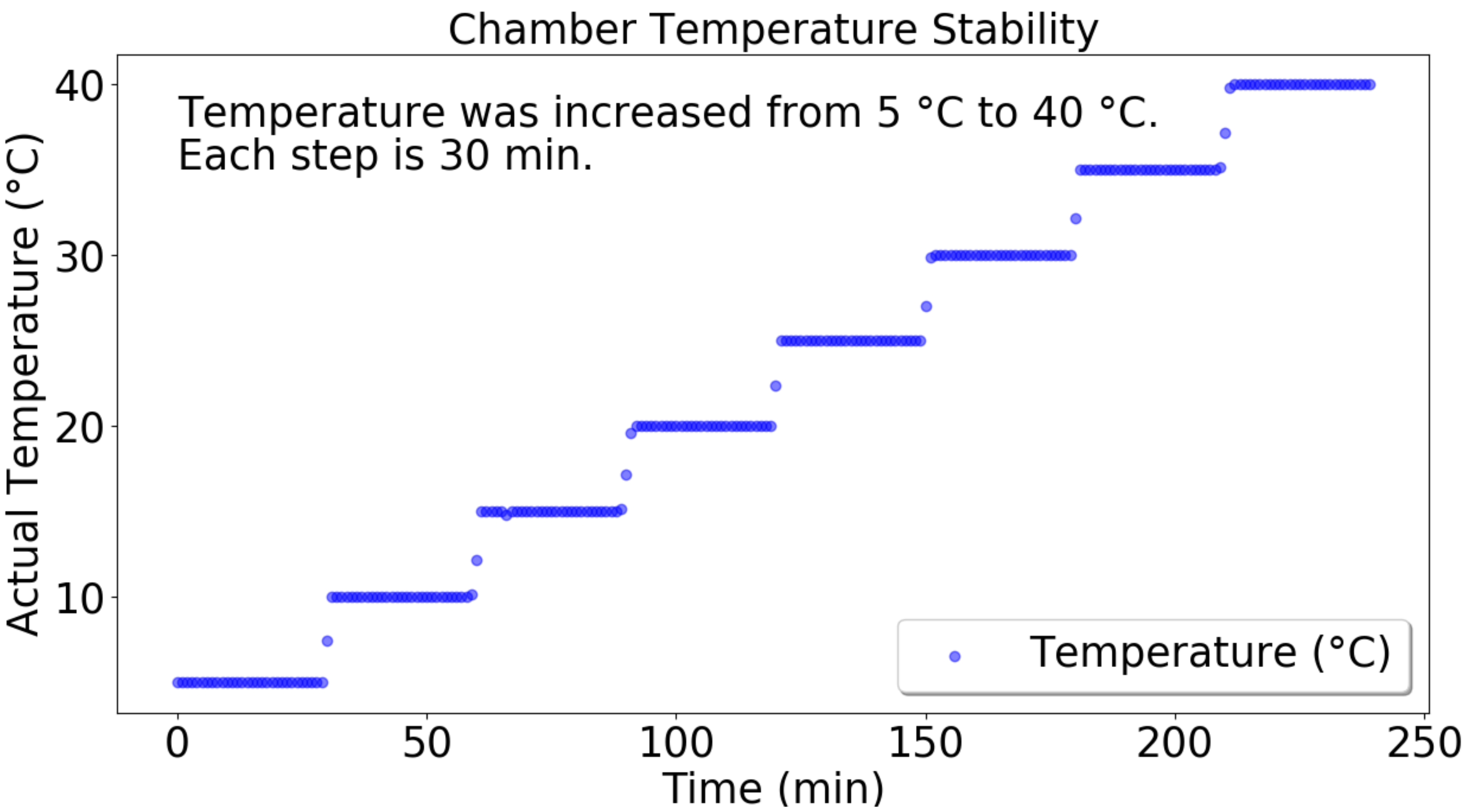


USB & power ports

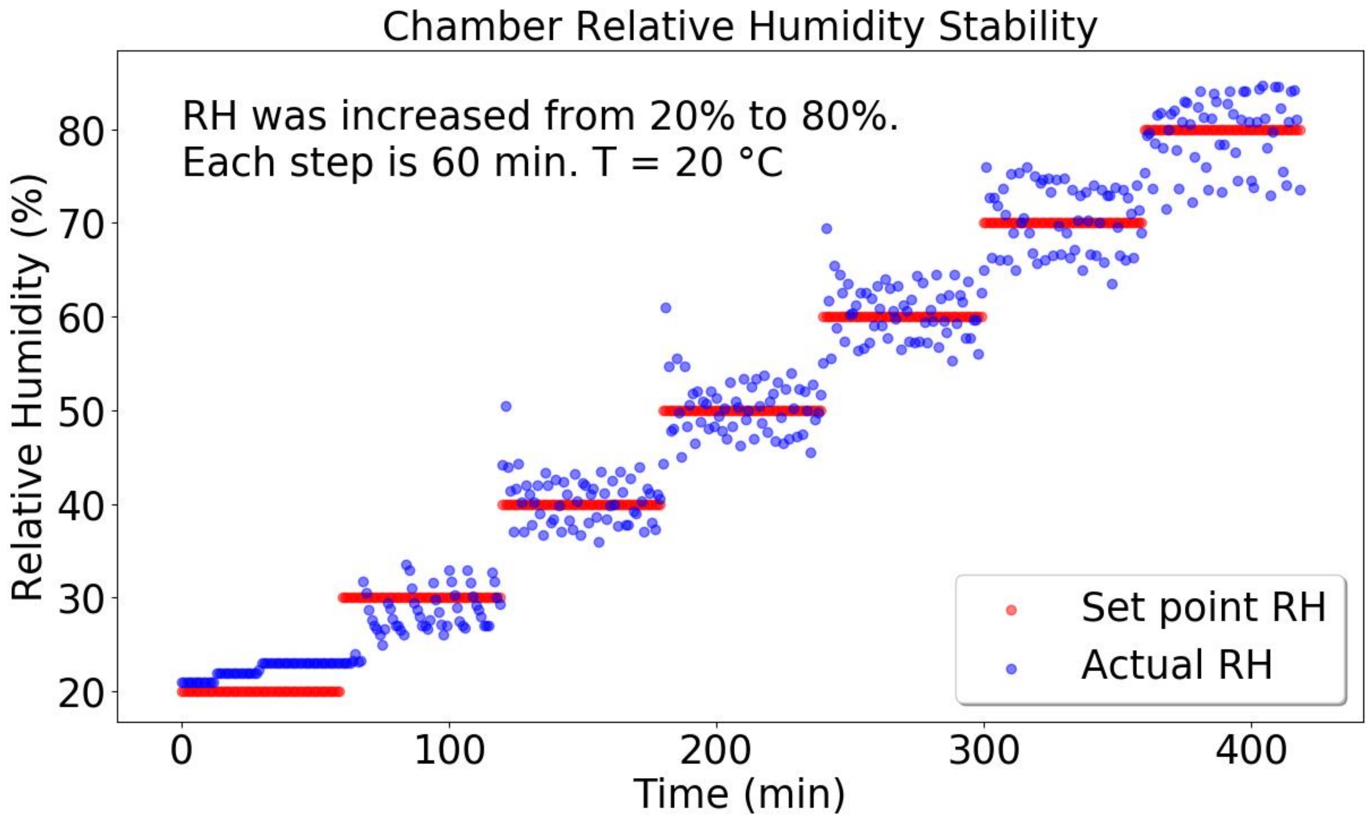


Wi Fi

Bluetooth™

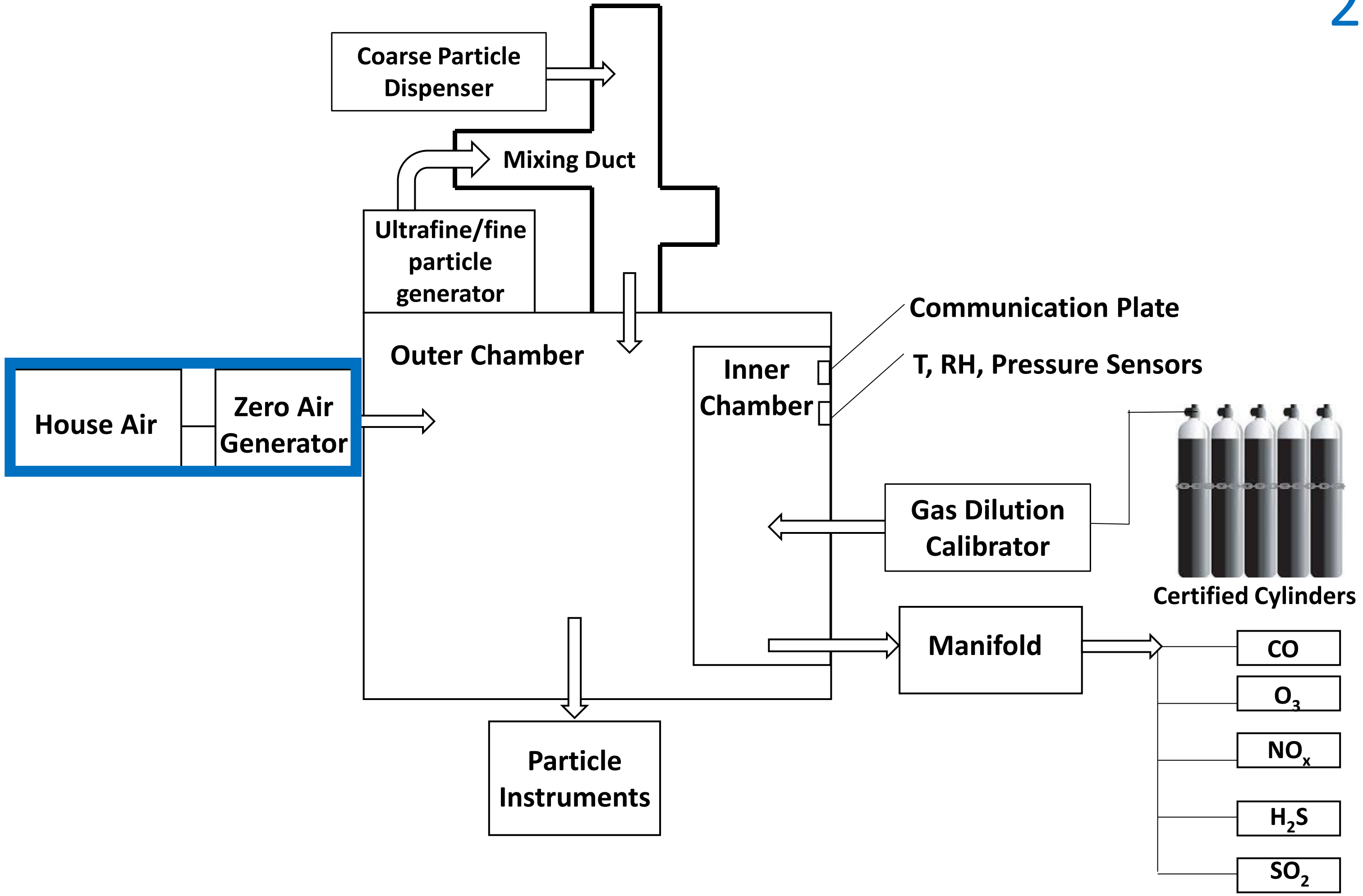


- Highly precise temperature control
- Temperature range: **- 32 to + 177 °C**

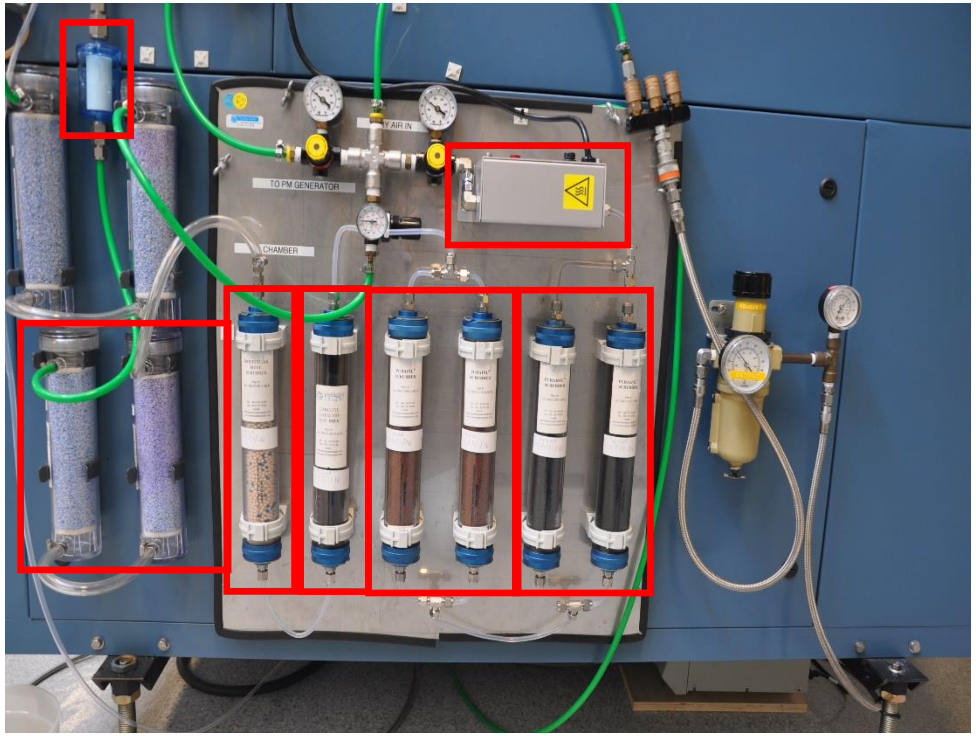


- More precise RH control at higher temp
- At 20 °C, SD range: ± 0.8% to ±3.5%
- At low temp and high RH, RH oscillates near set points, due to humidifying and dehumidifying cycle
- Relative Humidity range: **5 to 95 %**

2. "Zero air" generation system

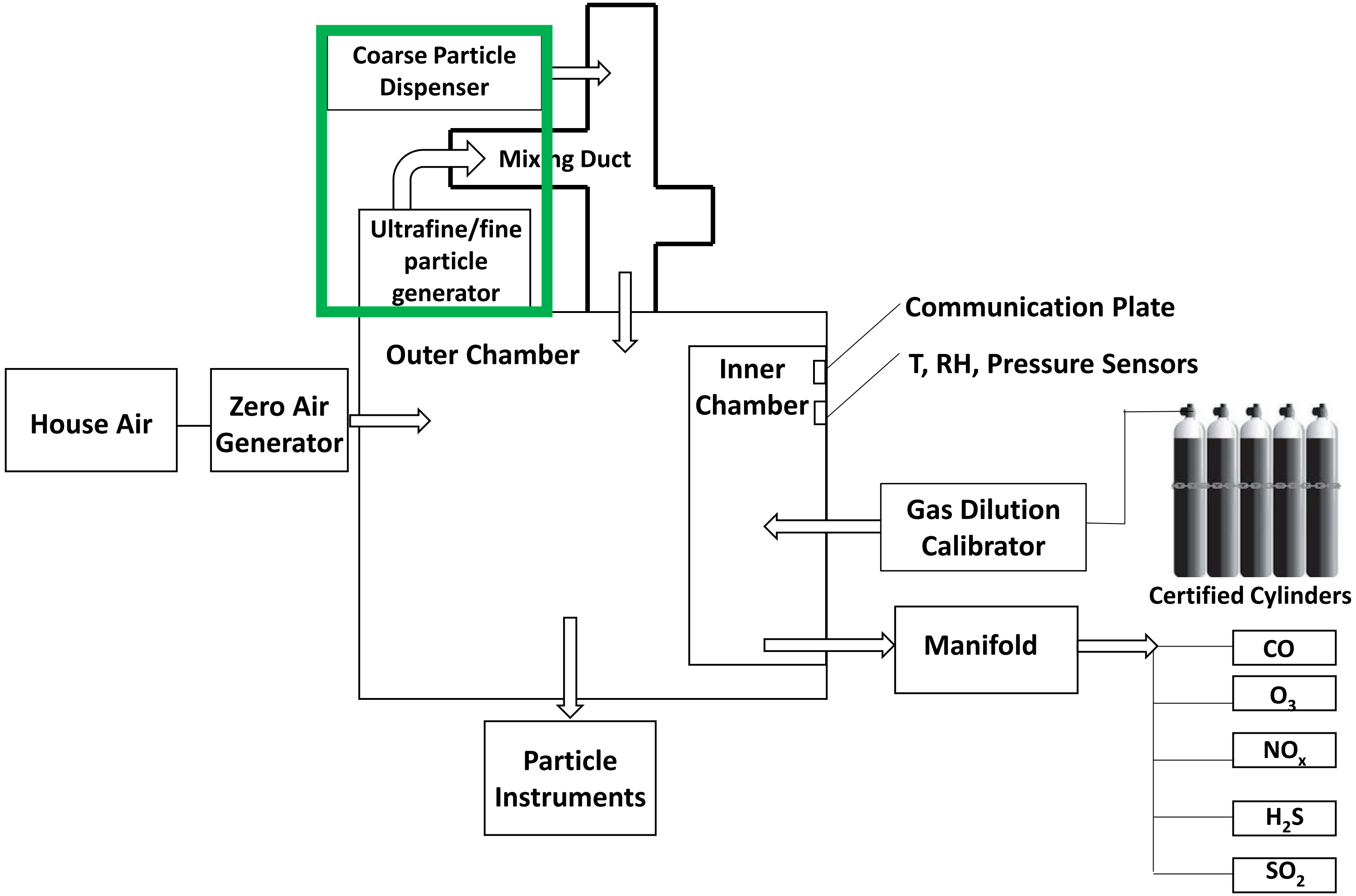


“Zero-Air” system: Dry, gas- and particle-free dilution air system

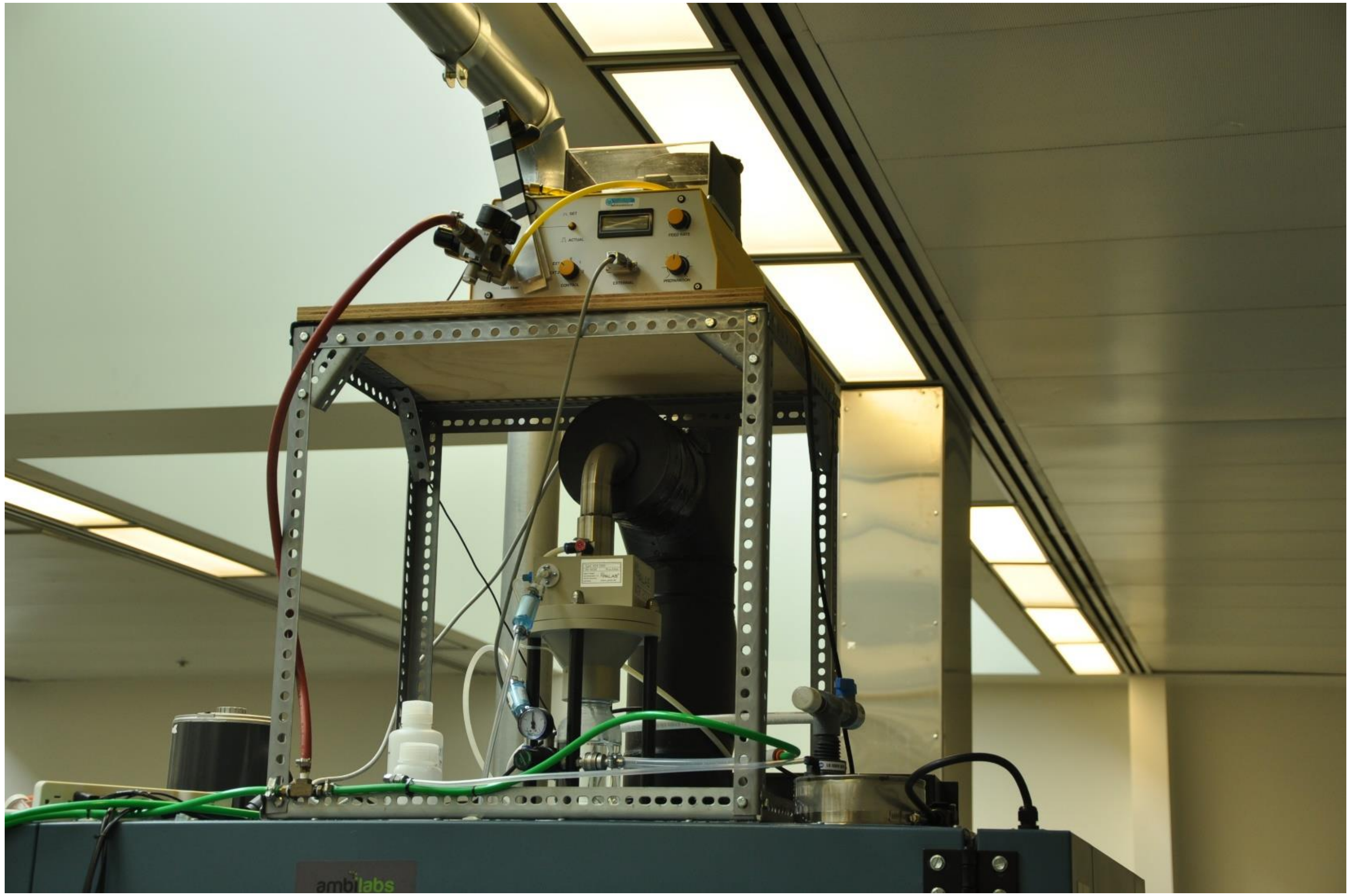


- One heated catalyst scrubber for the removal of CO
- Two scrubbers of activated carbon for the removal of VOC and NO_2
- Two scrubbers of $NaMNO_4$ impregnated on porous alumina (Purafil) for the removal of H_2S, SO_2, NO_x, and HCHO
- One cylinder of MnO_2/CuO catalyst for the removal of ozone O_3
- One cylinder of 13X molecular sieve
- Two cylinders of $CaSO_4$ to further dry the previously compressed and dried outside air
- One in-line HEPA filter for the removal of particulate impurities

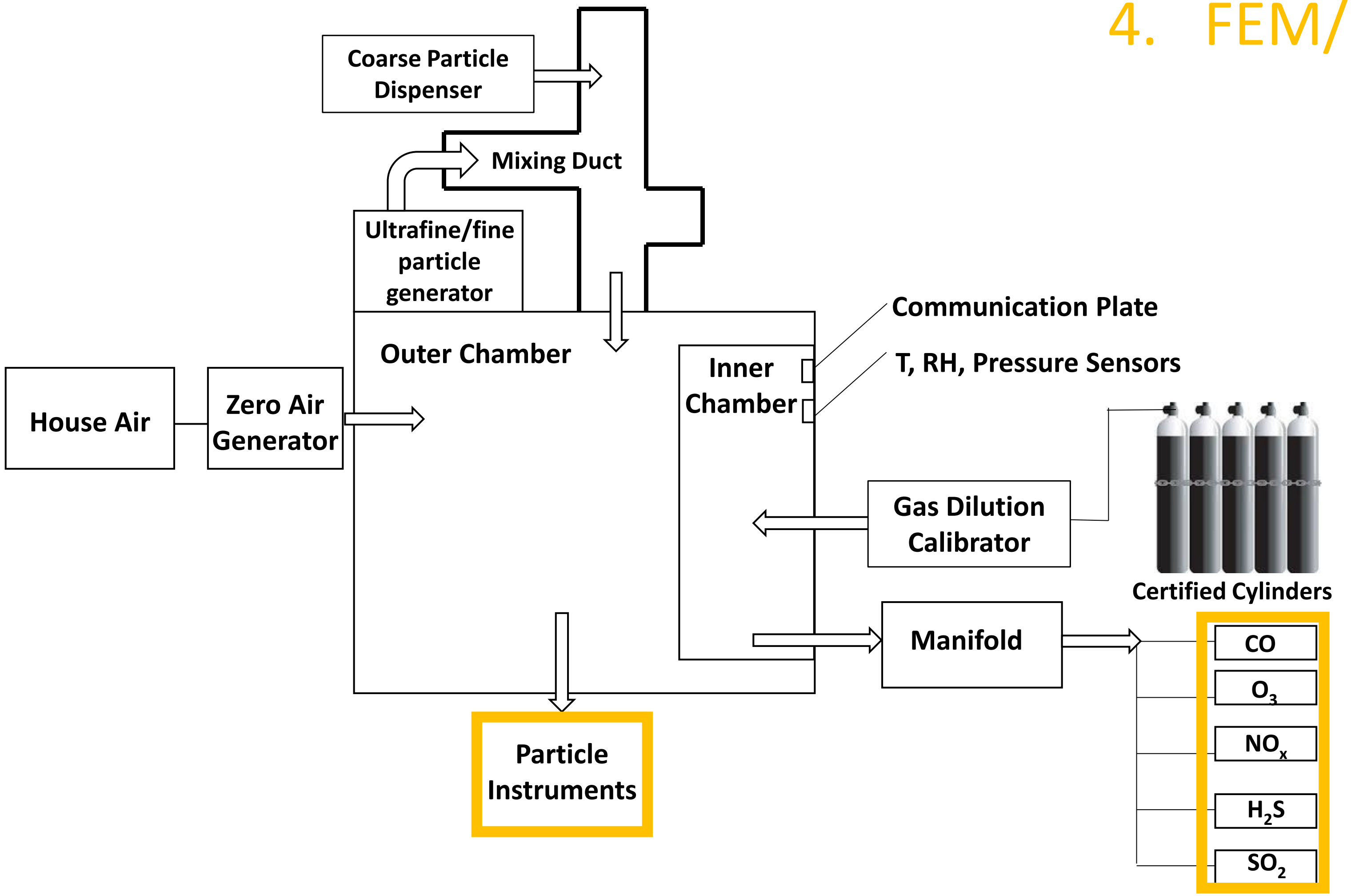
3. Two Particle systems




PALAS
AGK 2000



4. FEM/FRM/BAT reference instruments



Manufacturer	Model	Measures	Conc. Range	LDL	Measurement Technique
GRIMM	EDM180	PM_{10}, $PM_{2.5}$, and PM_1	0.1-1,500 µg/m^3	0.1 µg/m^3	light scattering
TSI	3321	0.5 to 20 µm	0-10,000 particles/m^3	0.001 particle/m^3	double-crest optical
TSI	3091	5.6 to 560 nm	N/A	N/A	electrical mobility
Teledyne	M651	ultrafine particle conc, > 7 nm	0.001 to 10^6 particles/cm^3	N/A	Water-based CPC

EDM 180 APS 3321

FMPS 3091

M651

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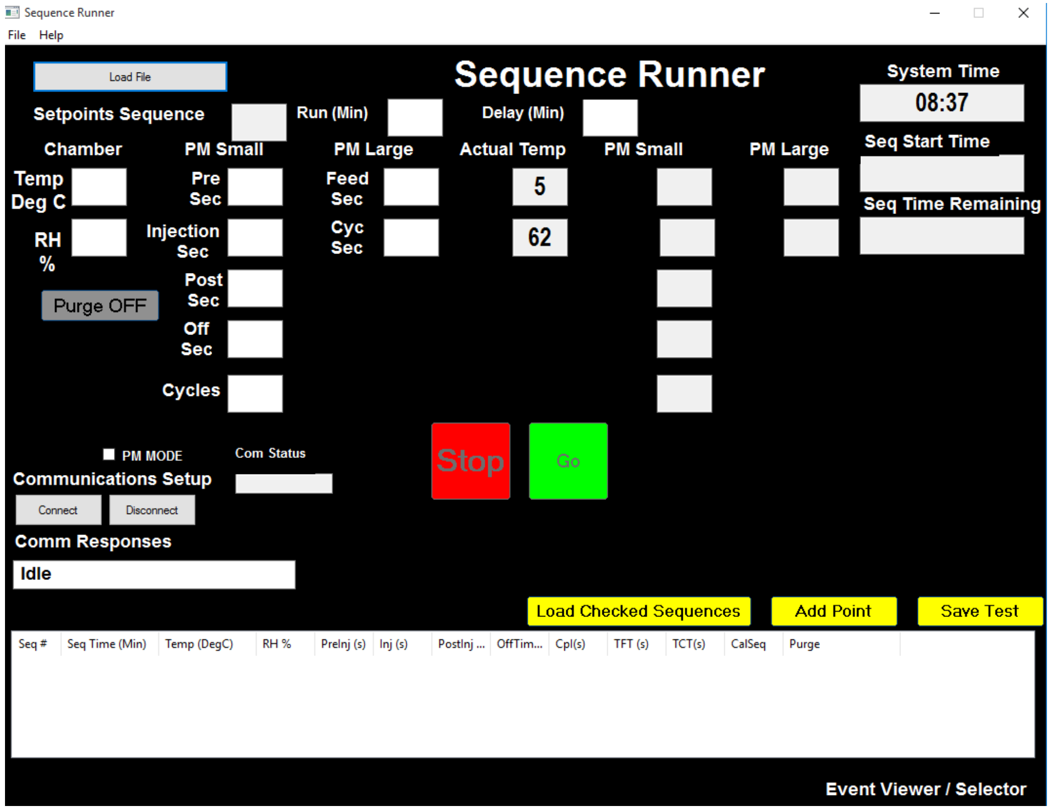
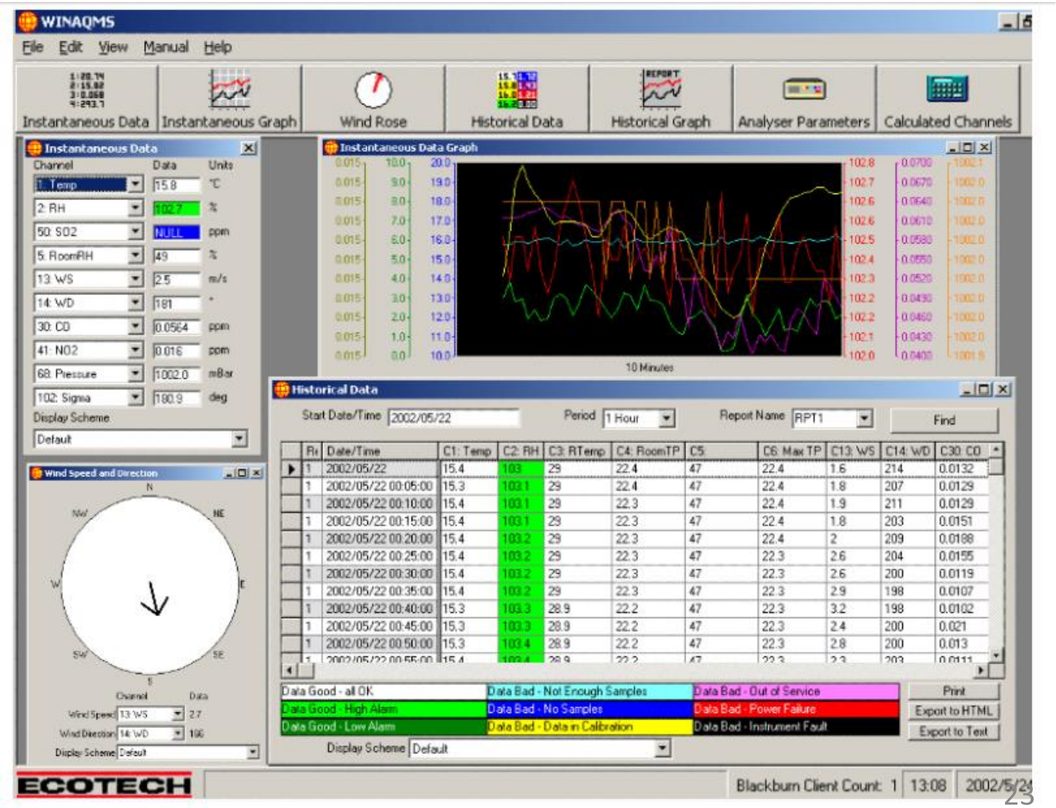
Particle systems control software



Gas analyzers and chamber Temp/RH sensors control software



T/RH combinations for sensor testing

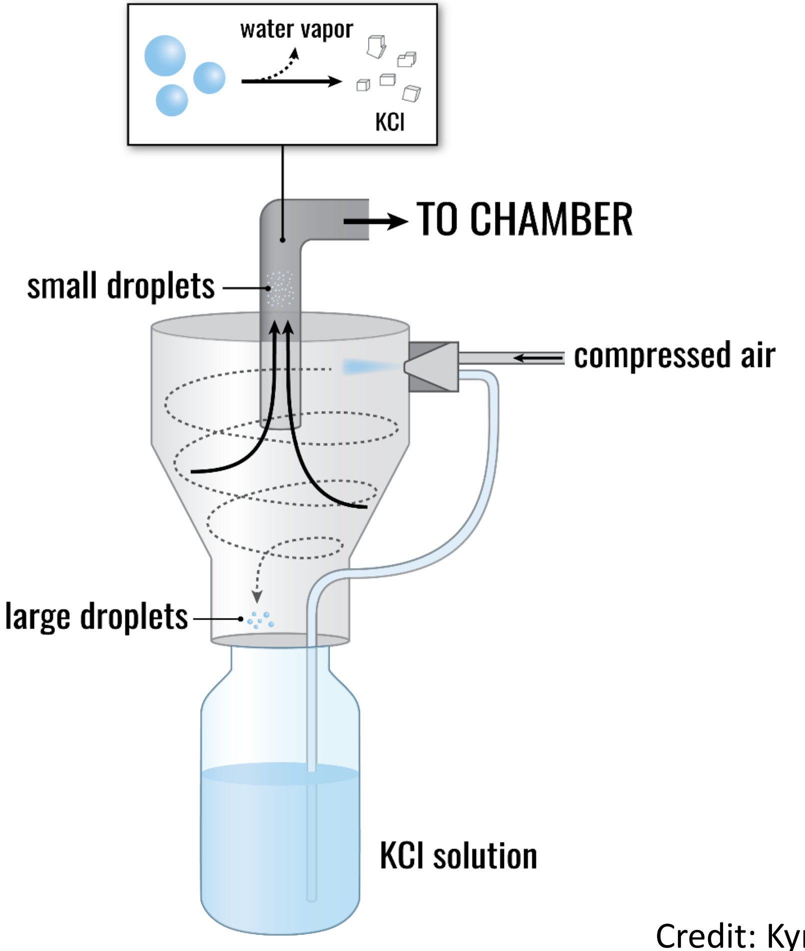
	Temperature (°C)		
Relative Humidity (%)	5 °C / 15% (Low / Low)	20 °C / 15%	35 °C / 15%
	5 °C / 40%	20 °C / 40%	35 °C / 40%
	5 °C / 65%	20 °C / 65%	35 °C / 65% (High / High)

	$PM_{2.5}/PM_{10}$
Level	(µg/m^3)
Very low	10
Low	15
Medium	50
High	150
Very High	300

- Particle systems (i.e., PALAS and TOPAS)
  - Theory of operation
  - Factors in determining aerosol concentrations (i.e., recipes)
  - Aerosol atmospheres
    - Stability
    - Reproducibility
    - Decay experiment
  - Particle size distribution
- Sensor evaluation experiments - Examples

Papapostolou V, Zhang H, Feenstra B and Polidori A. 2017. Development of an Environmental Chamber for the Laboratory Evaluation of "Low-Cost" Air Quality Sensors, *Atmospheric Environment*, 171: 82-90

Aerosol Generation System



Credit: Kyrstin Fornace

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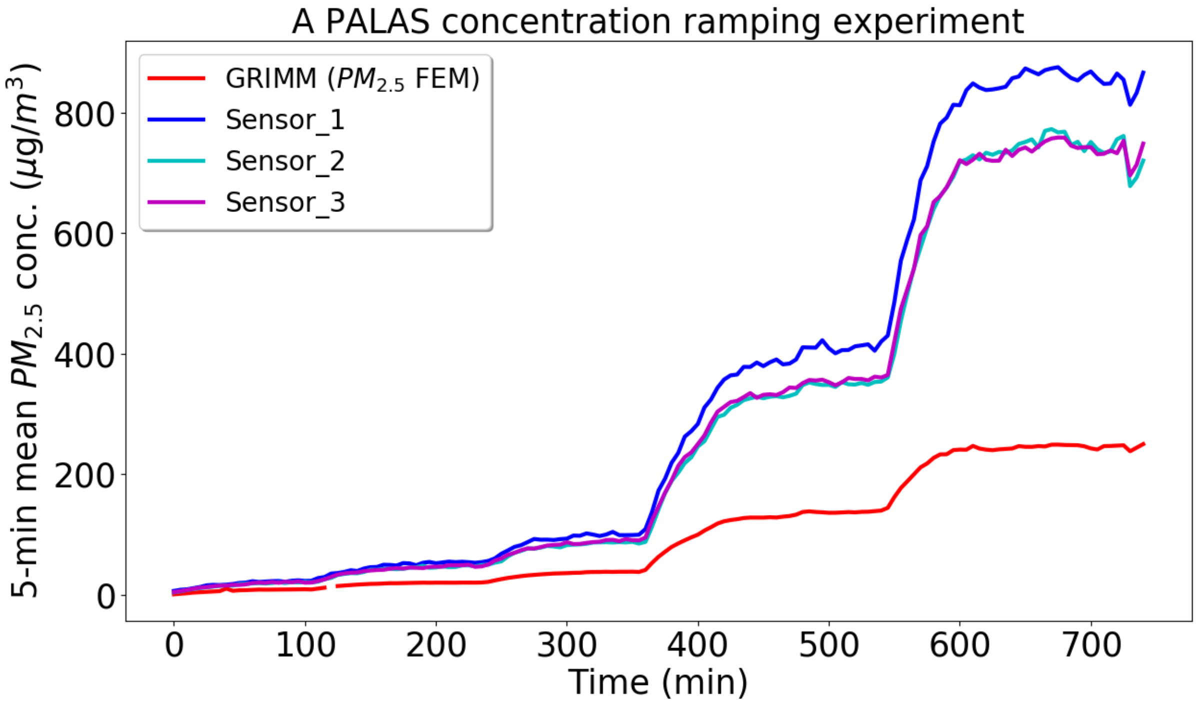
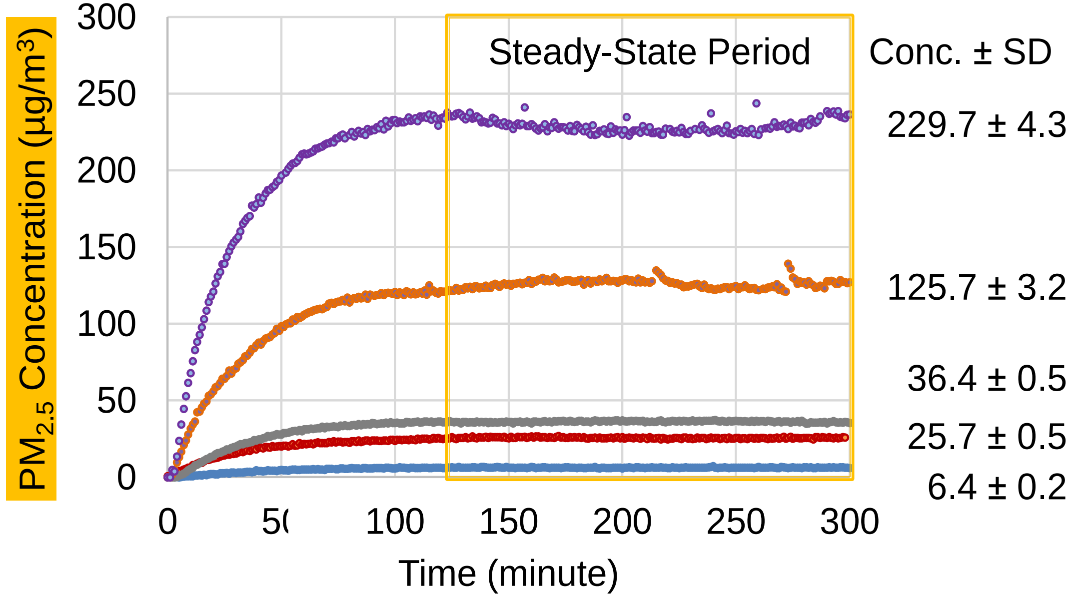
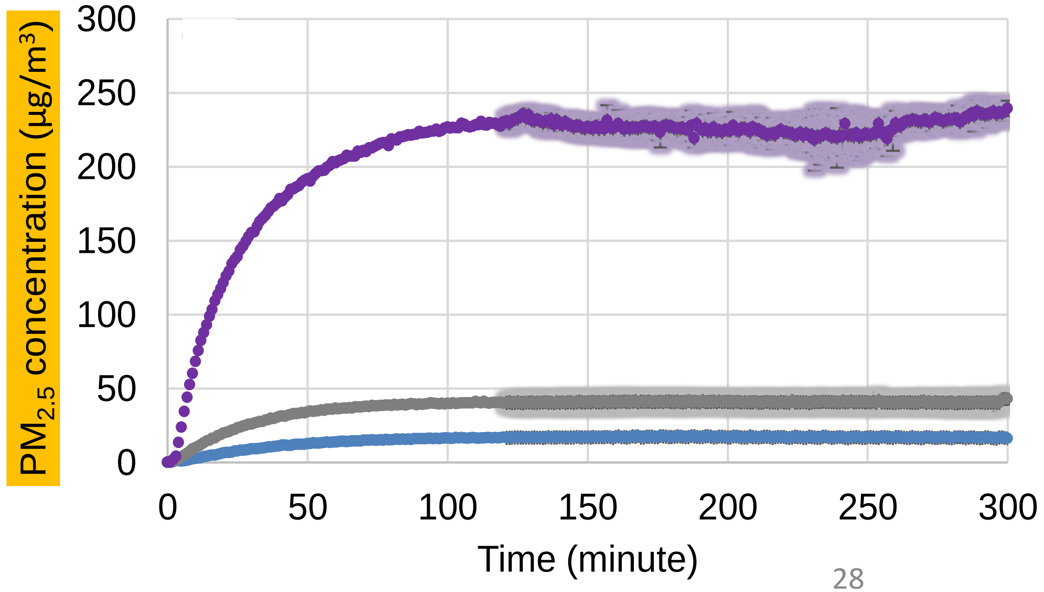
Factors in determining aerosol conc.:

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

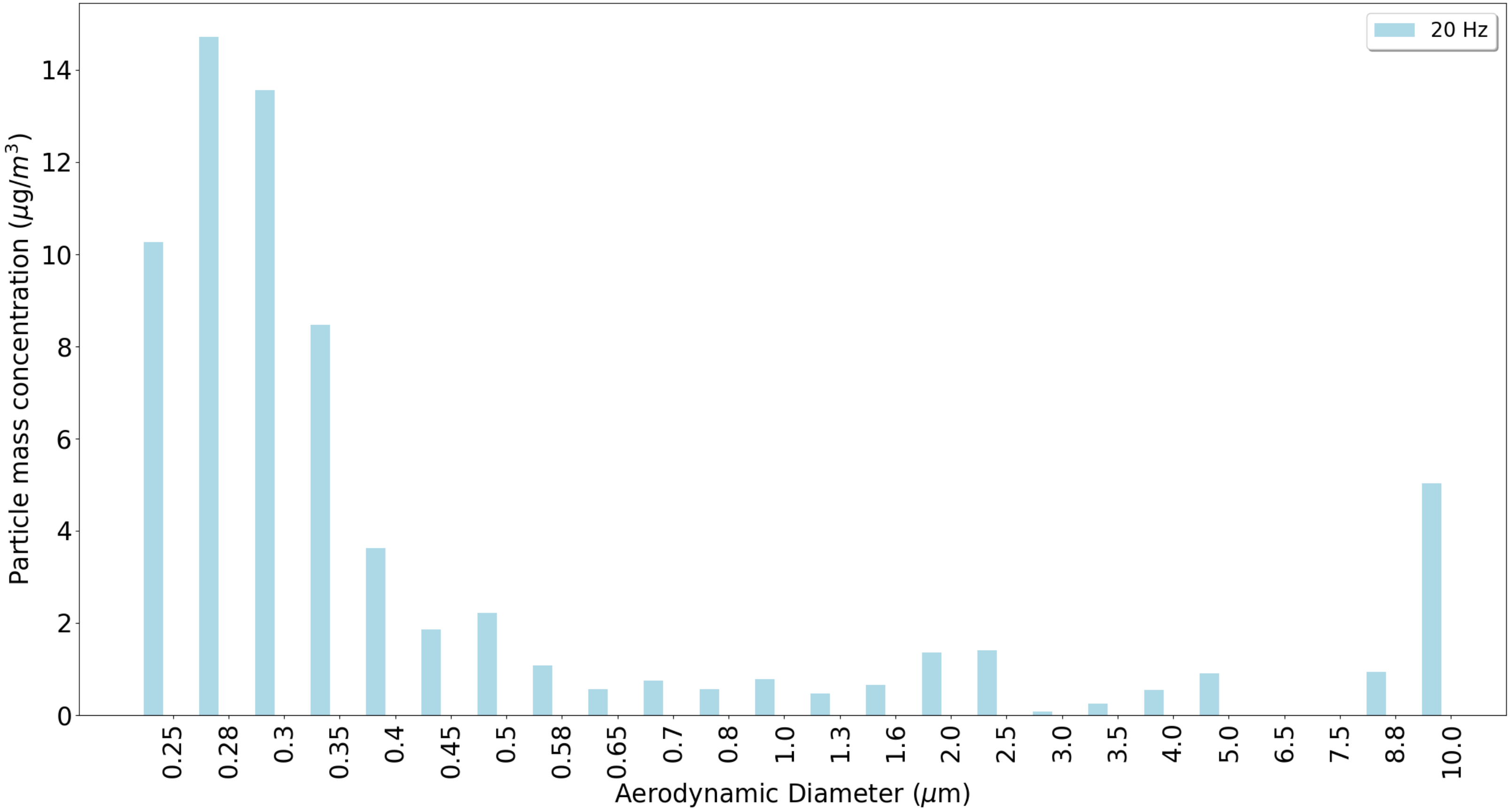


	pre-inj	inj	post-inj	off	cycle
step 1	1	1	1	32	4
step 2	1	1	1	32	2
step 3	1	1	1	32	0
step 4	1	2	1	32	0
step 5	1	4	1	32	0

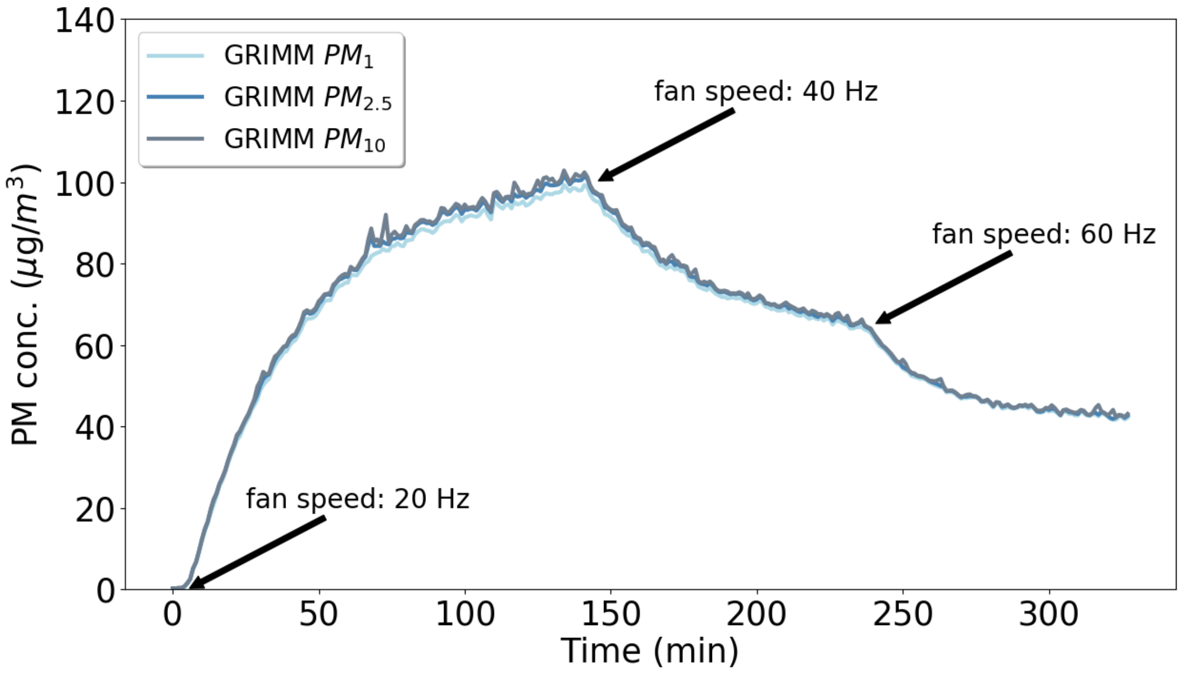


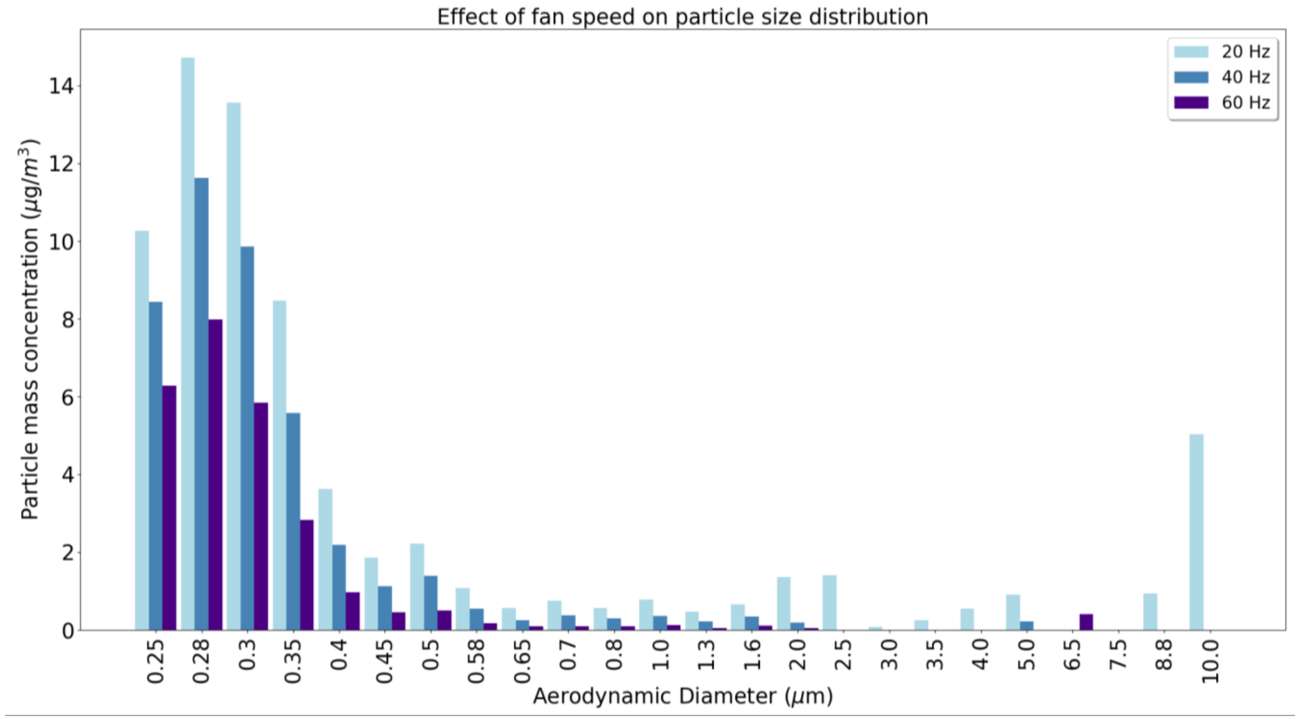


- Wide range of concentrations: 6 – 230 µg/m^3
- Stability (5 different experiments, 300 min each)
- Reproducibility (3 repeated experiments, shaded area is std error)

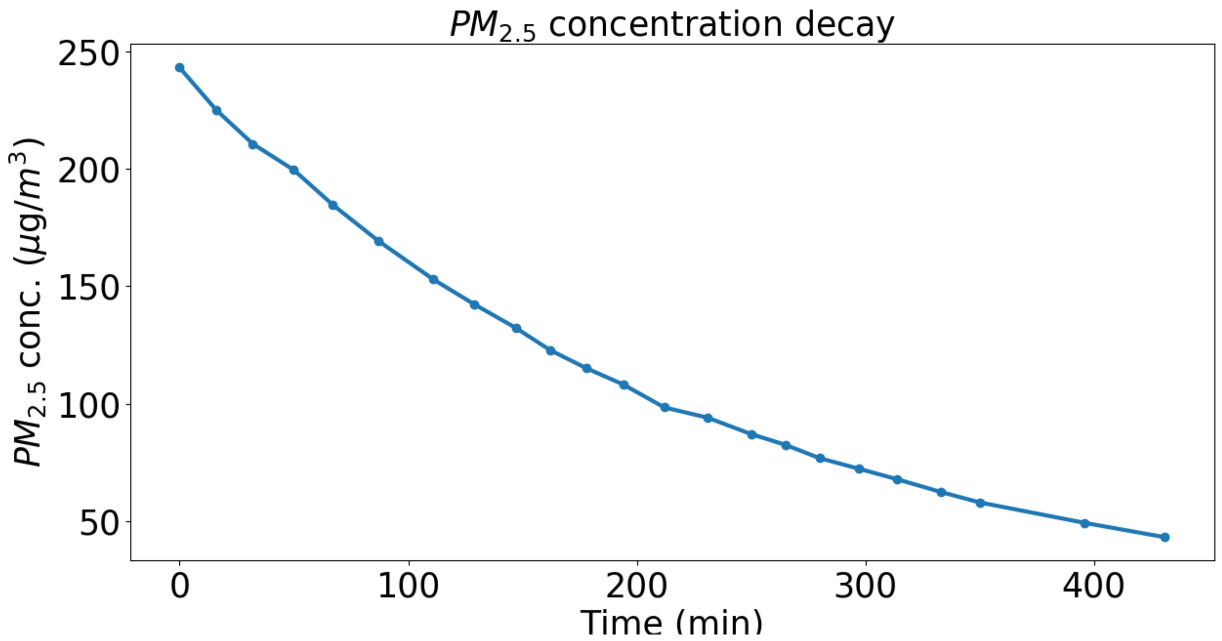


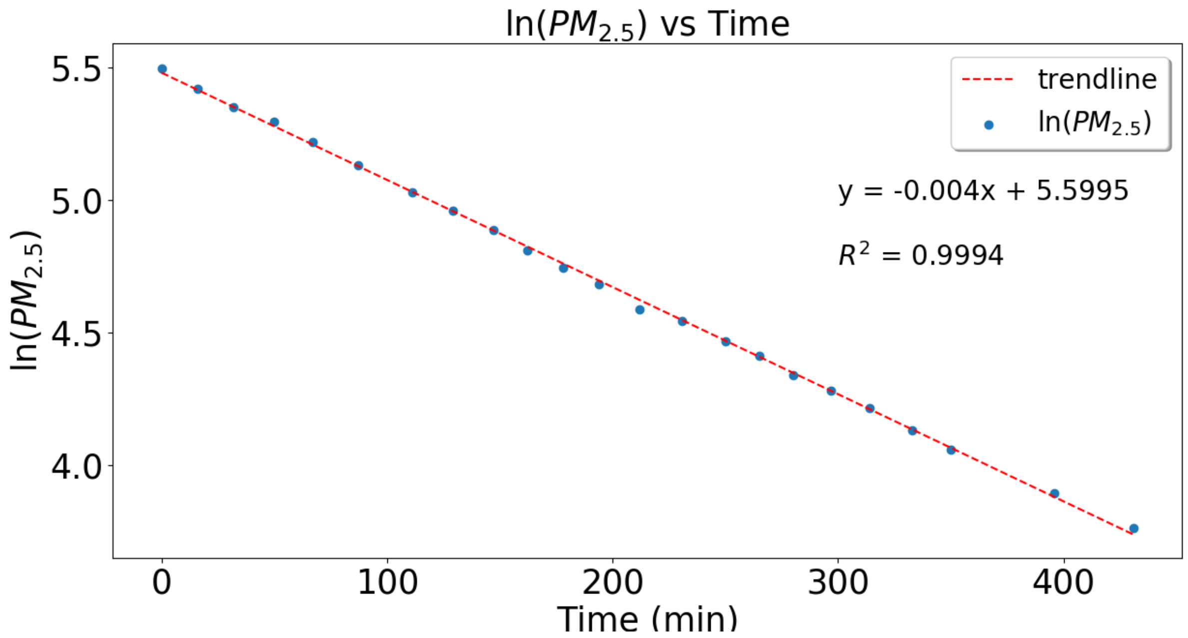
- 100 µg/m^3
- GRIMM EDM180
- 0.25-32 µm in aerodynamic particle diameters
- 31 in total size channels





- T = 0 min, started experiment, fans frequency at 20 Hz
- T = 150 min, adjusted to 40 Hz
- T = 210 min, adjusted to 60 Hz


$PM_{2.5}$ concentration decay
$PM_{2.5}$ conc. ($\mu g/m^3$)
Time (min)
250
200
150
100
50
0
100
200
300
400


ln($PM_{2.5}$) vs Time
ln($PM_{2.5}$)
Time (min)
trendline
ln($PM_{2.5}$)
y = -0.004x + 5.5995
R^2 = 0.9994
5.5
5.0
4.5
4.0
0
100
200
300
400

Dust dispenser

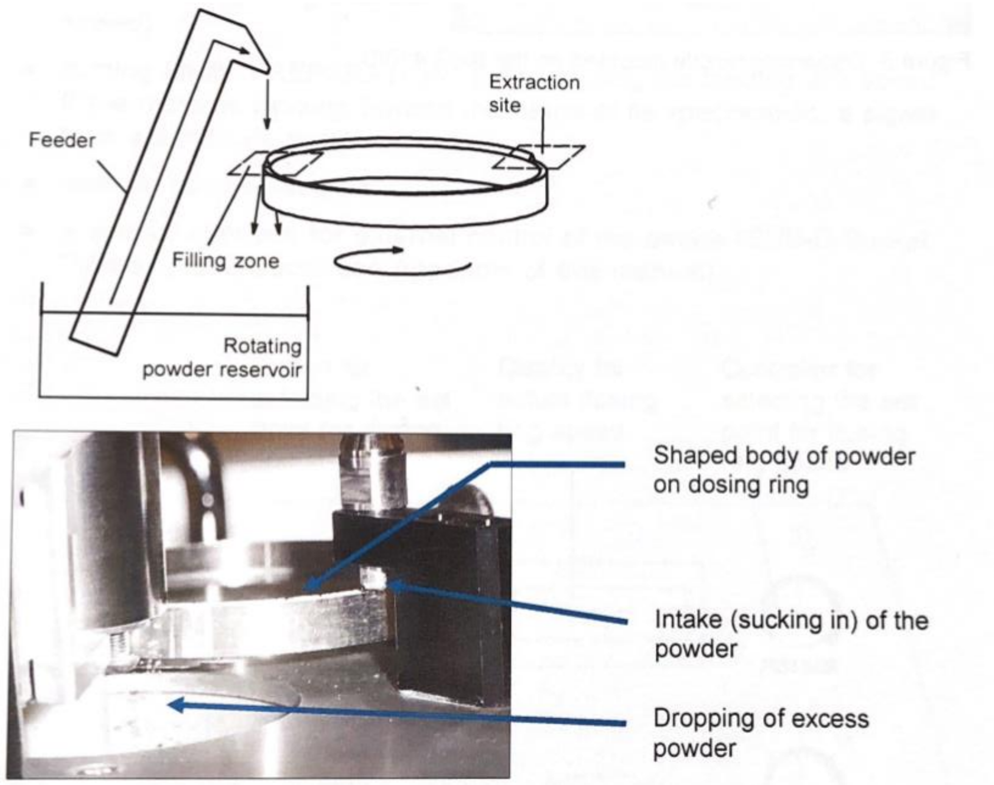
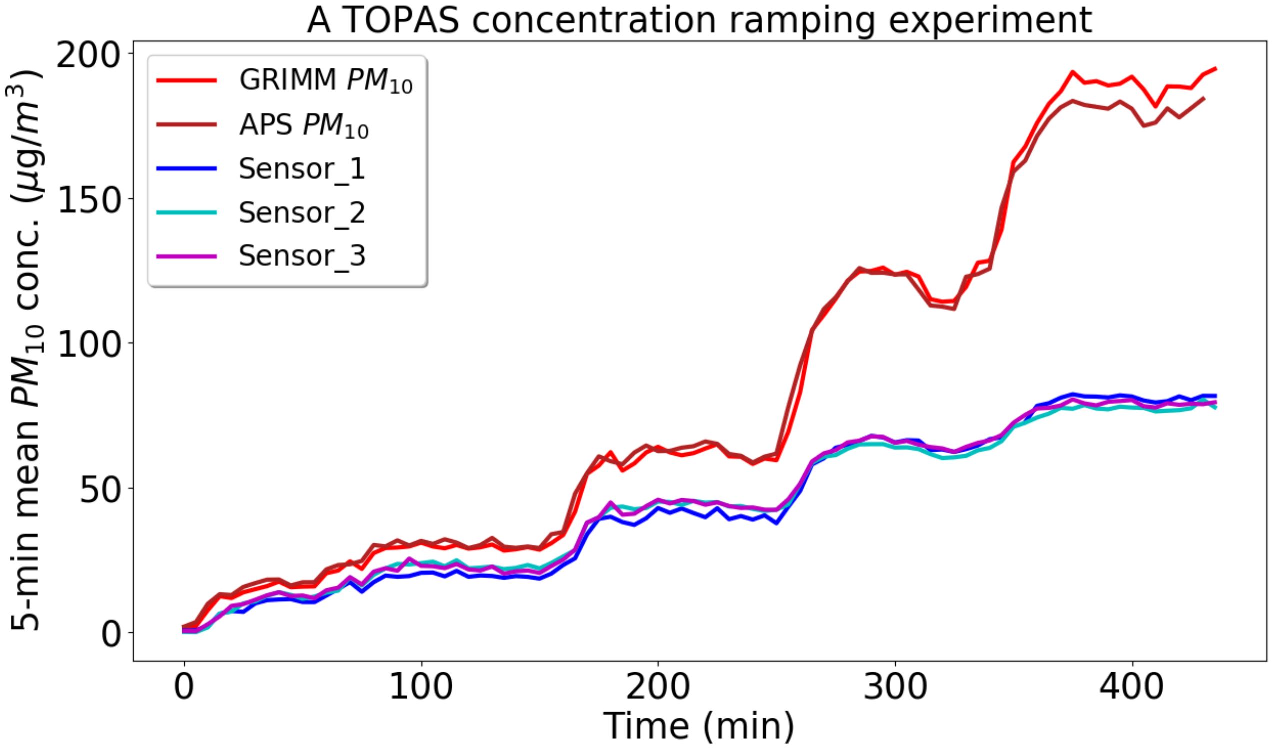


Figure 4: Principle of the SAG 410/U

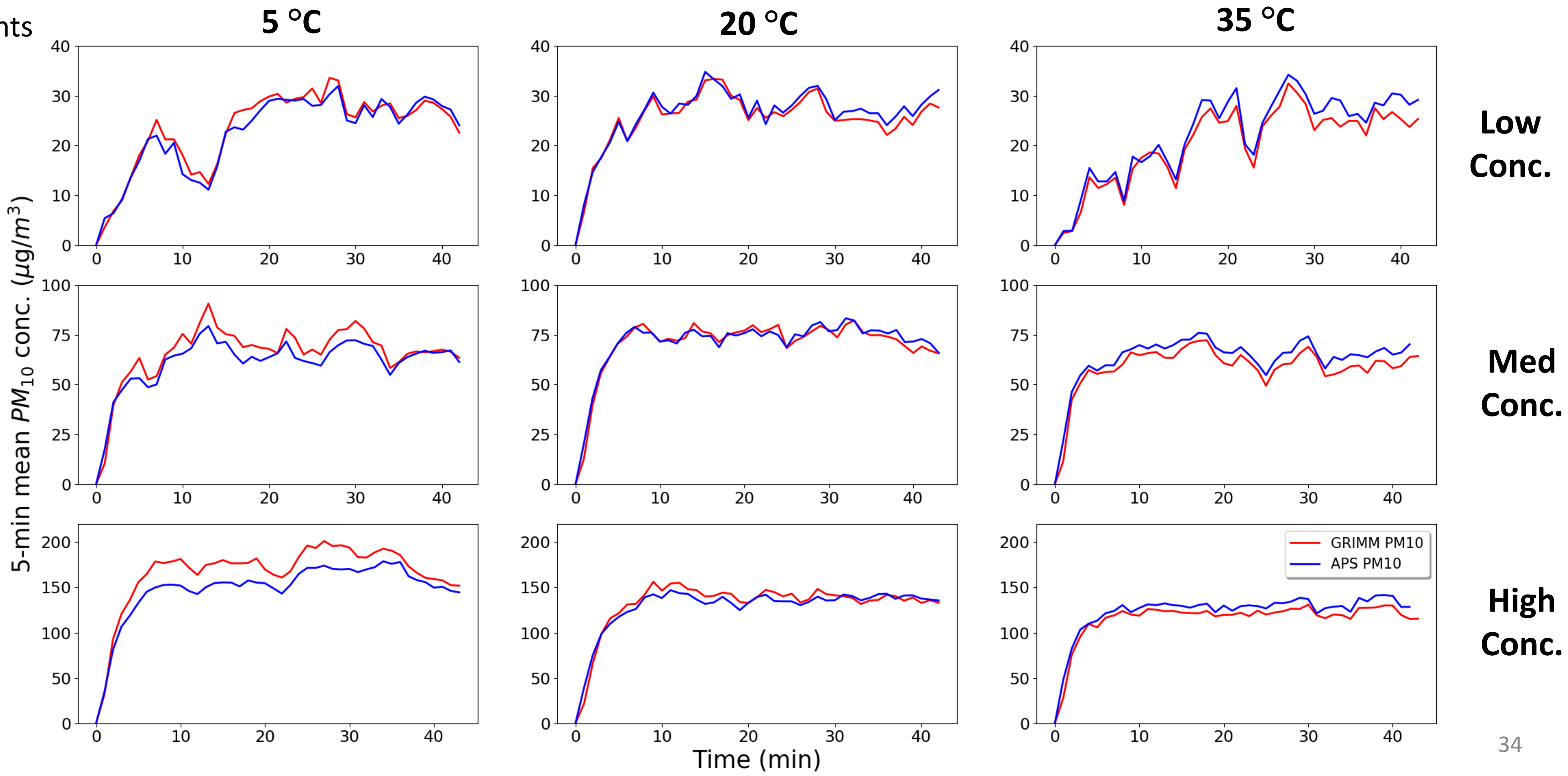
- ISO 12103-A4 (Coarse) Arizona Test Dust
- Dryness (Hygroscopicity) of the standard dust
  - Dust is vacuum dried prior to use
  - Dust box is purged with dry air continuously
- Feeding belt speed (%)
- Chamber fans speed

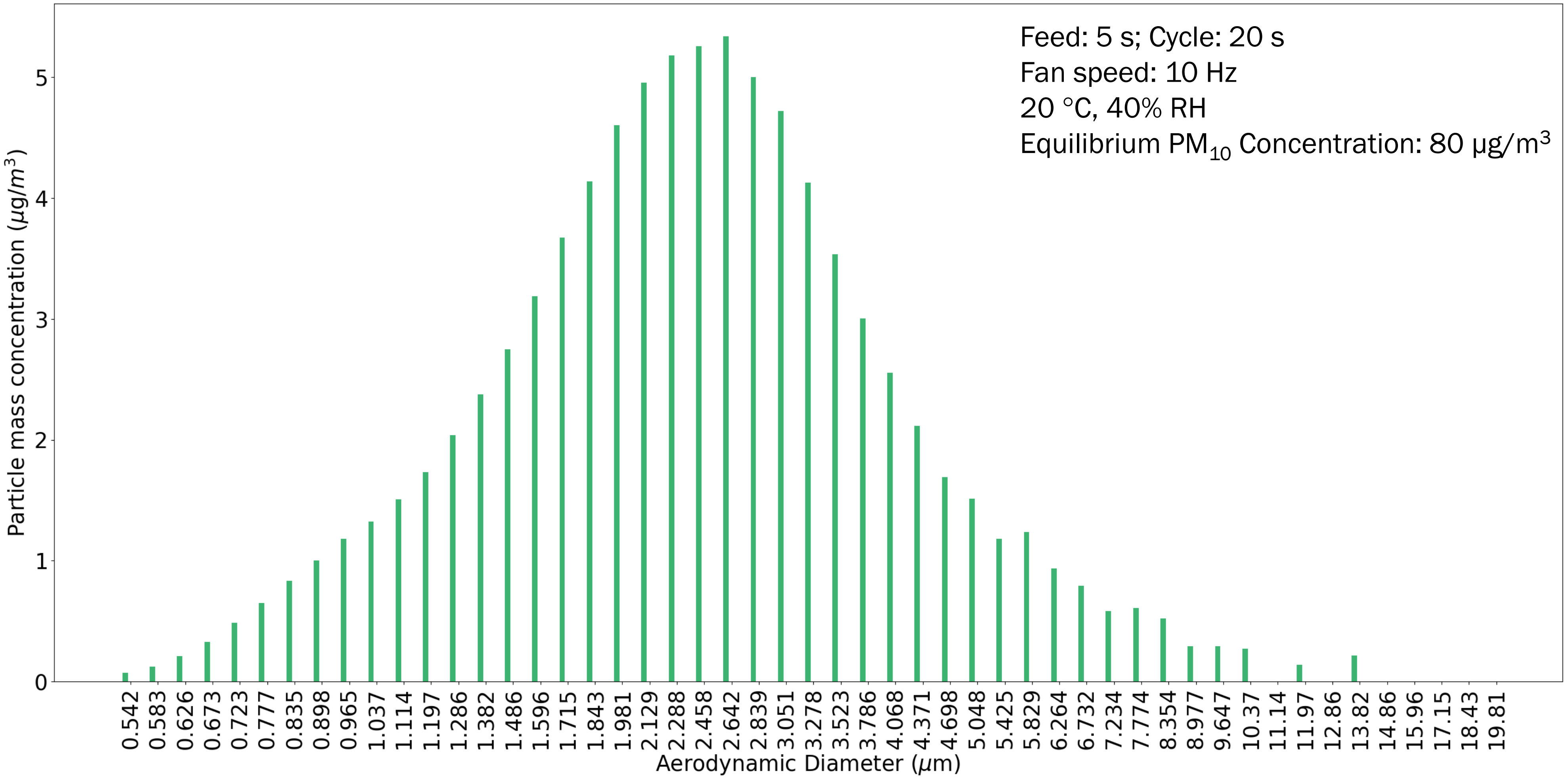
APS conc. is corrected for ATD density (2.6 g/cm^3)

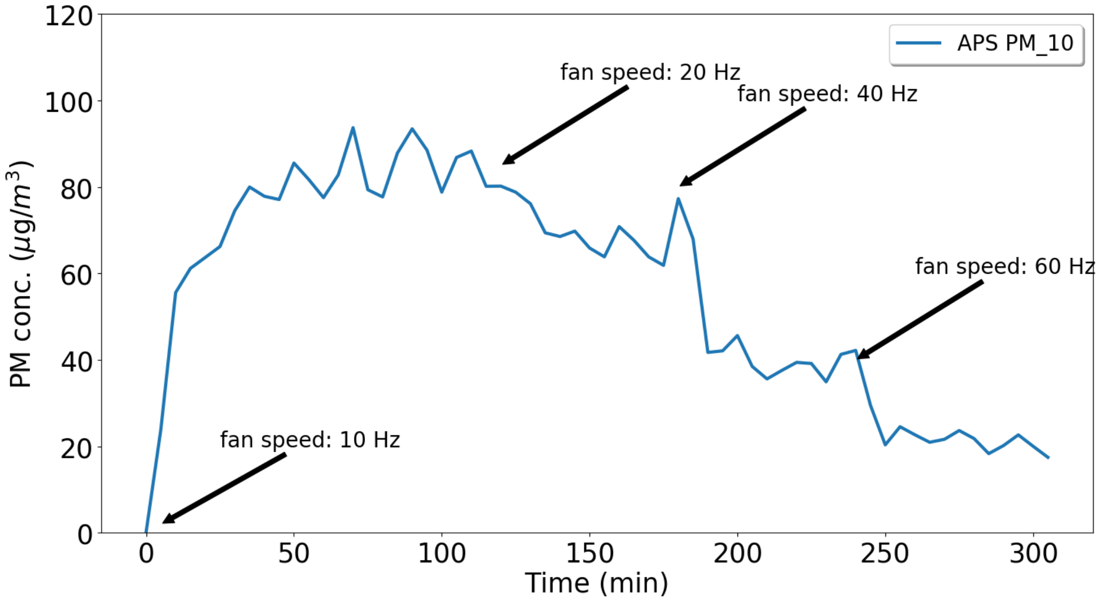
	Feed (s)	Cycle (s)
step 1	1	30
step 2	1	20
step 3	2	20
step 4	4	20
step 5	6	20

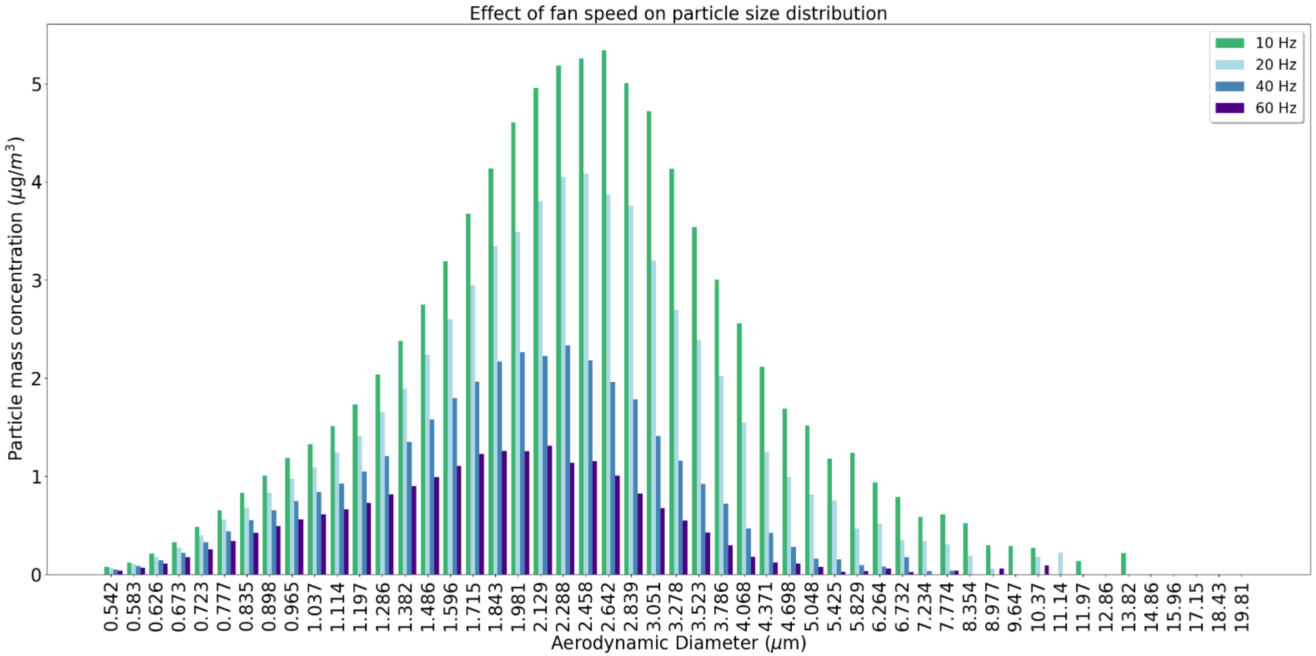


Relative Humidity
Ramping Experiments
15% to 40% to 65%

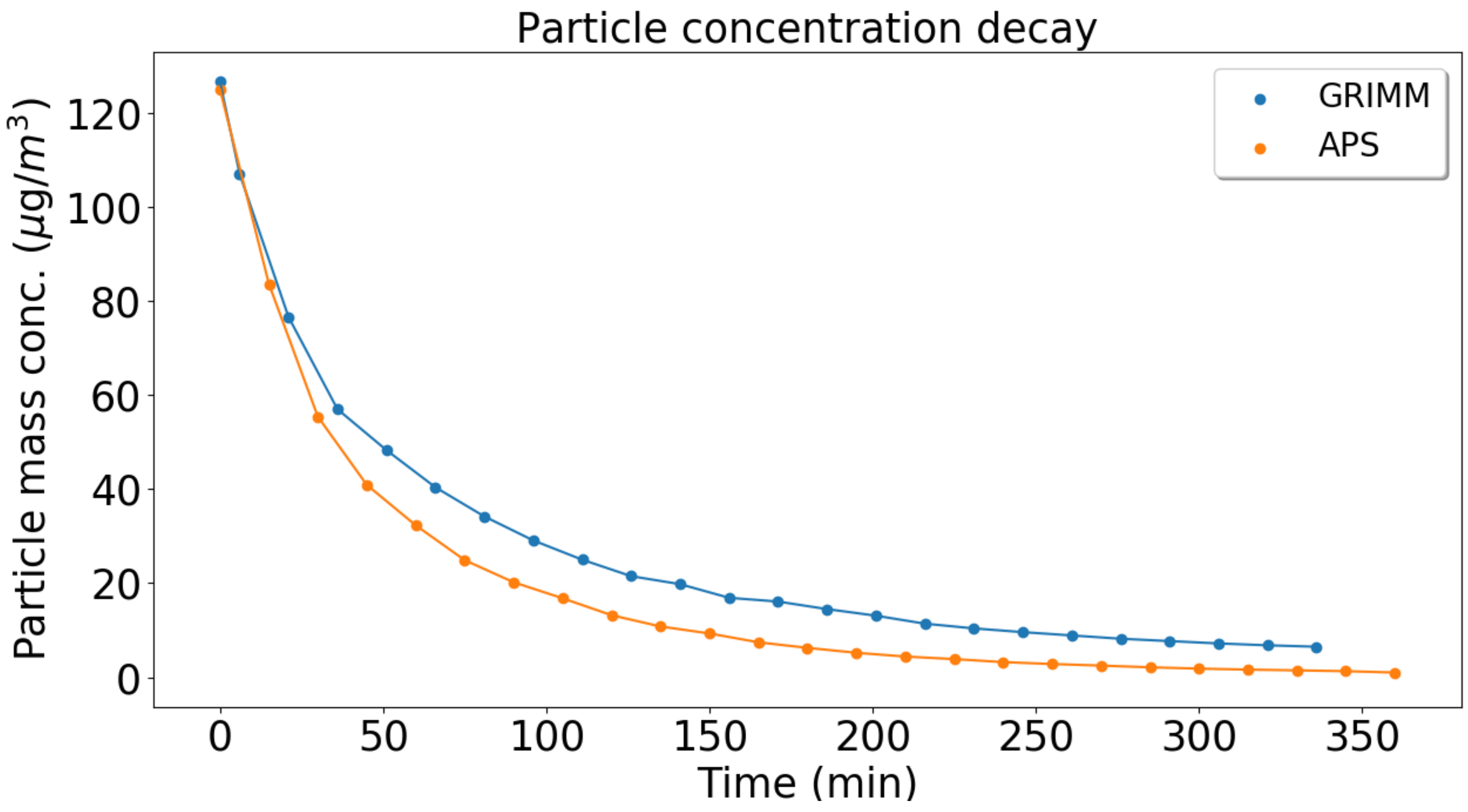



Feed: 5 s; Cycle: 20 s
Fan speed: 10 Hz
20 °C, 40% RH
Equilibrium PM_{10} Concentration: 80 µg/m^3
Particle mass concentration ($\mu g/m^3$)
0
1
2
3
4
5
0.542
0.583
0.626
0.673
0.723
0.777
0.835
0.898
0.965
1.037
1.114
1.197
1.286
1.382
1.486
1.596
1.715
1.843
1.981
2.129
2.288
2.458
2.642
2.839
3.051
3.278
3.523
3.786
4.068
4.371
4.698
5.048
5.425
5.829
6.264
6.732
7.234
7.774
8.354
8.977
9.647
10.37
11.14
11.97
12.86
13.82
14.86
15.96
17.15
18.43
19.81
Aerodynamic Diameter (μm)





- T = 0 min started experiment at 10Hz (Feed 5s; Cycle 20s), 80 μg/m^3
- T = 120 min, adjusted frequency at 20 Hz, 62 μg/m^3
- T = 180 min, adjusted frequency at 40 Hz, 41 μg/m^3
- T = 240 min, adjusted frequency at 60 Hz, 23 μg/m^3


Particle concentration decay
GRIMM
APS
Particle mass conc. ($\mu g/m^3$)
Time (min)
0
20
40
60
80
100
120
0
50
100
150
200
250
300
350

T/RH combinations for sensor testing

	Temperature (°C)		
Relative Humidity (%)	5 °C / 15% (Low / Low)	20 °C / 15%	35 °C / 15%
	5 °C / 40%	20 °C / 40%	35 °C / 40%
	5 °C / 65%	20 °C / 65%	35 °C / 65% (High / High)

Pollutant	PM
Level/units	(µg/m³)
Very low	10
Low	15
Medium	50
High	150
Very High	300

Evaluation Parameters:

- ✓ Intra-model variability
- ✓ Accuracy
- ✓ Precision
- ✓ Coefficient of Determination (R^2)
- ✓ Data Recovery
- ✓ Climate Susceptibility
- ✓ Interferents (e.g., monodisperse aerosols)

Polidori A, Papapostolou V, Zhang H. 2016. AQ-SPEC Laboratory Evaluation of Low-cost Air Quality Sensors – Laboratory Setup and Testing Protocol (Diamond Bar, CA)

$$\text{Intra-model variability (\%)} = \frac{\text{Mean}_{\text{highest}} - \text{Mean}_{\text{lowest}}}{\text{Mean}_{\text{average}}} * 100$$

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

Accuracy

$$A\ (\%) = 100 - \frac{|\overline{X} - \overline{R}|}{\overline{R}} * 100$$

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

Precision

$$P\,(\%) = 100 - \frac{\overline{SE_{sensor}}}{\overline{X}} * 100$$

where,

$\overline{SE_{sensor}}$ is the standard error of the averaged concentrations of the three sensors during the steady-state period considered
$\overline{X}$ is the average concentration measured by the three sensors throughout the same steady-state period

$$SE_{sensor} = \frac{\sqrt{\Sigma\,(X-\overline{X})^2}}{n}$$

where,

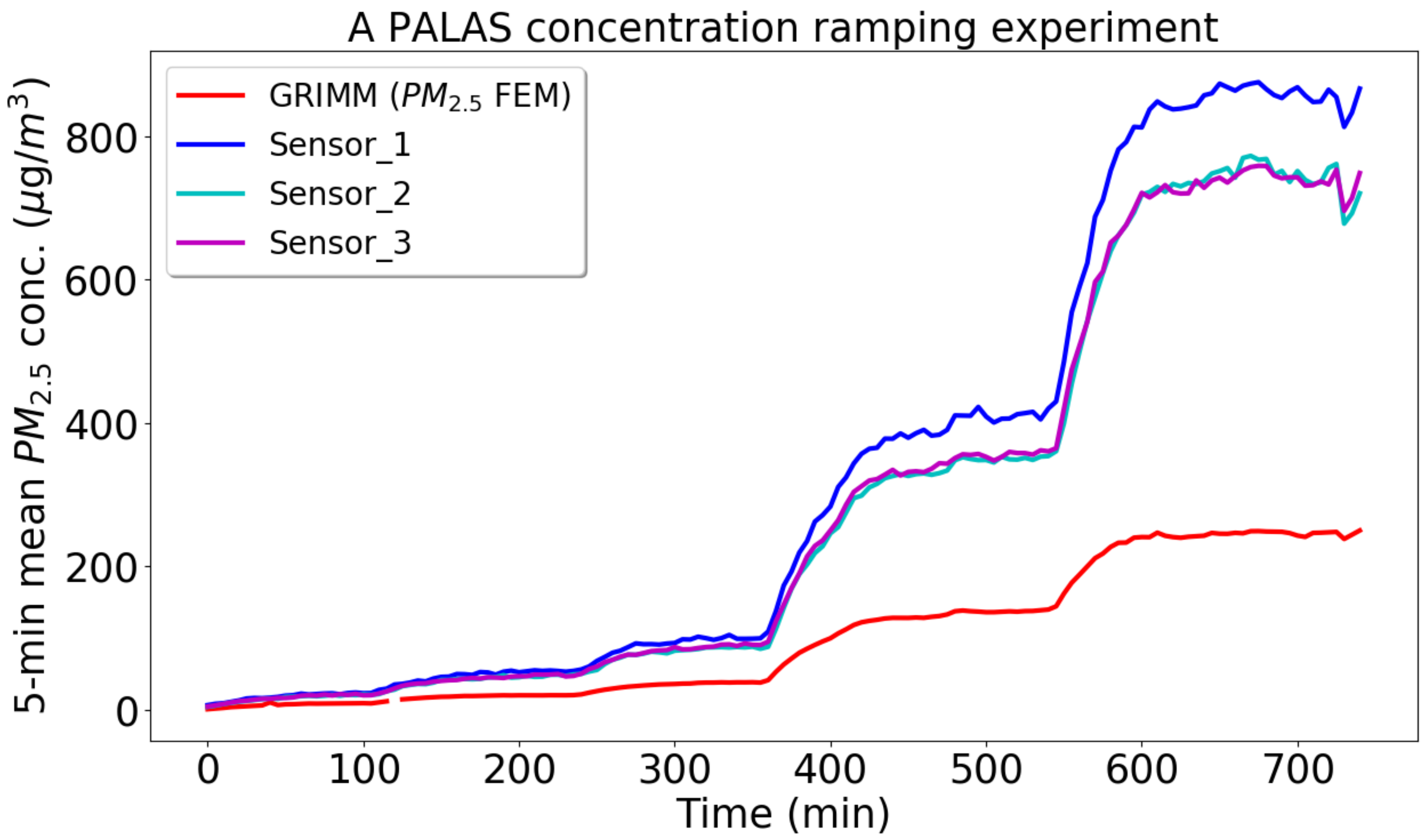
X is the average value of the three sensors concentrations at different times during the steady-state period considered
$\overline{X}$ is the average concentration measured by the three sensors throughout the same steady-state period

Coefficient of Determination (R^2)

- 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 R^2 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)

$$\text{Data recovery (\%)} = \frac{N_{\text{valid data}}}{N_{\text{test period}}} * 100$$

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
GRIMM ($PM_{2.5}$ FEM)
Sensor_1
Sensor_2
Sensor_3
5-min mean $PM_{2.5}$ conc. ($\mu g/m^3$)
0
200
400
600
800
0
100
200
300
400
500
600
700
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 CH_4 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?

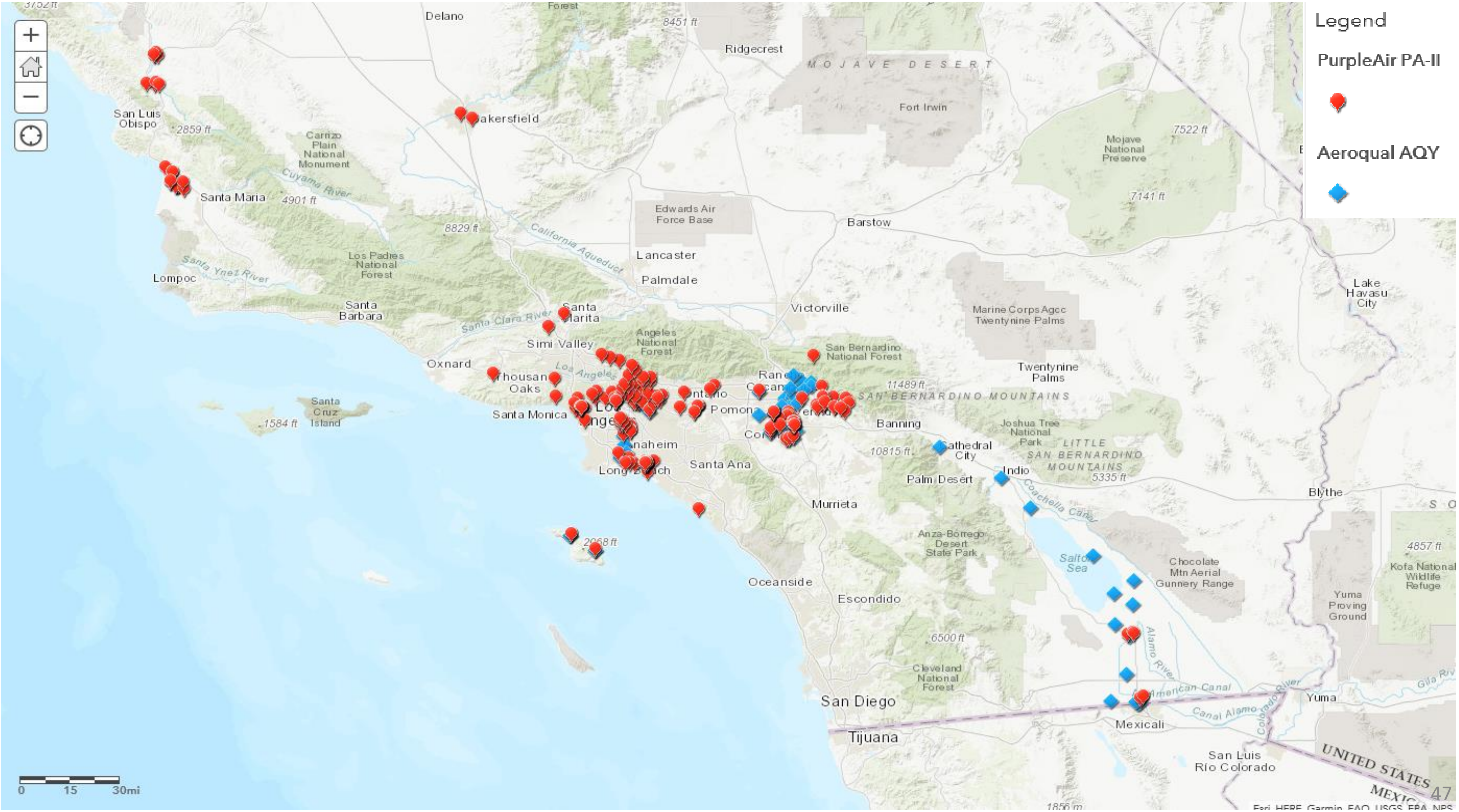


- Which pollutant(s) / sensor type(s)?
  - Are PM (e.g., particle counters) and Ozone (e.g., electrochemical) sensors good candidates?
- “Certified” for which use/application?
  - Regulatory?
  - Permitting?
  - Fenceline?
  - Citizen science?
  - Community monitoring?
  - Other?

…….for what?

- 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:
  - Data completeness
  - Long-term drift
  - Between instrument uncertainty
  - Expanded uncertainty
- No field pre-calibration:
  - Coefficient of determination (R^2)

4. Algorithms:

- Correct interferences (e.g., RH), part of field calibration?
- AI function:
  - Pre-set and applied during field calibration?
  - 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. …???

Hagler GSW, Williams R, Papapostolou V, Polidori A. 2018. Air Quality Sensors and Data Adjustment Algorithms: When Is It No Longer a Measurement? *Environmental Science & Technology*, DOI: 10.1021/acs.est.8b01826

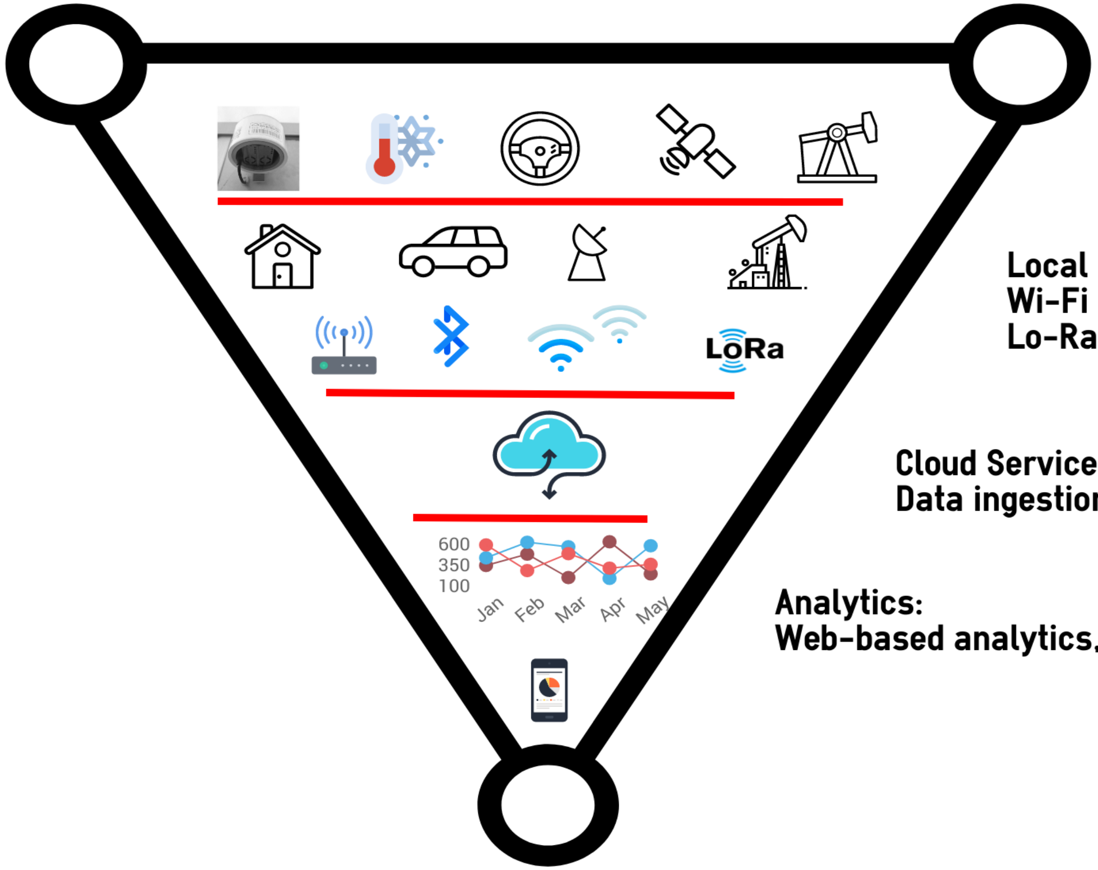
Outline

- 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

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

Fence-line monitoring	Regional monitoring network	US EPA STAR grant community monitoring	Future monitoring projects
9 PM sensors	~ 100 nodes Measures • O_3, NO_2, & PM	~ 390 PM sensors in 14 communities	Hotspot identification
IoT vendor platform		Wi-Fi connected	Mobile monitoring
Cellular to SaaS	Cellular to PaaS	Data sent to: • PurpleAir Map • AQMD Azure	AB617 community monitoring
API Access	API access		SCAQMD Rule 1180 implementation

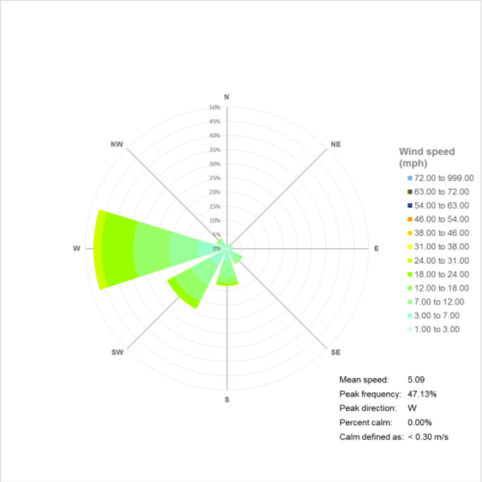
Fence-line Monitoring

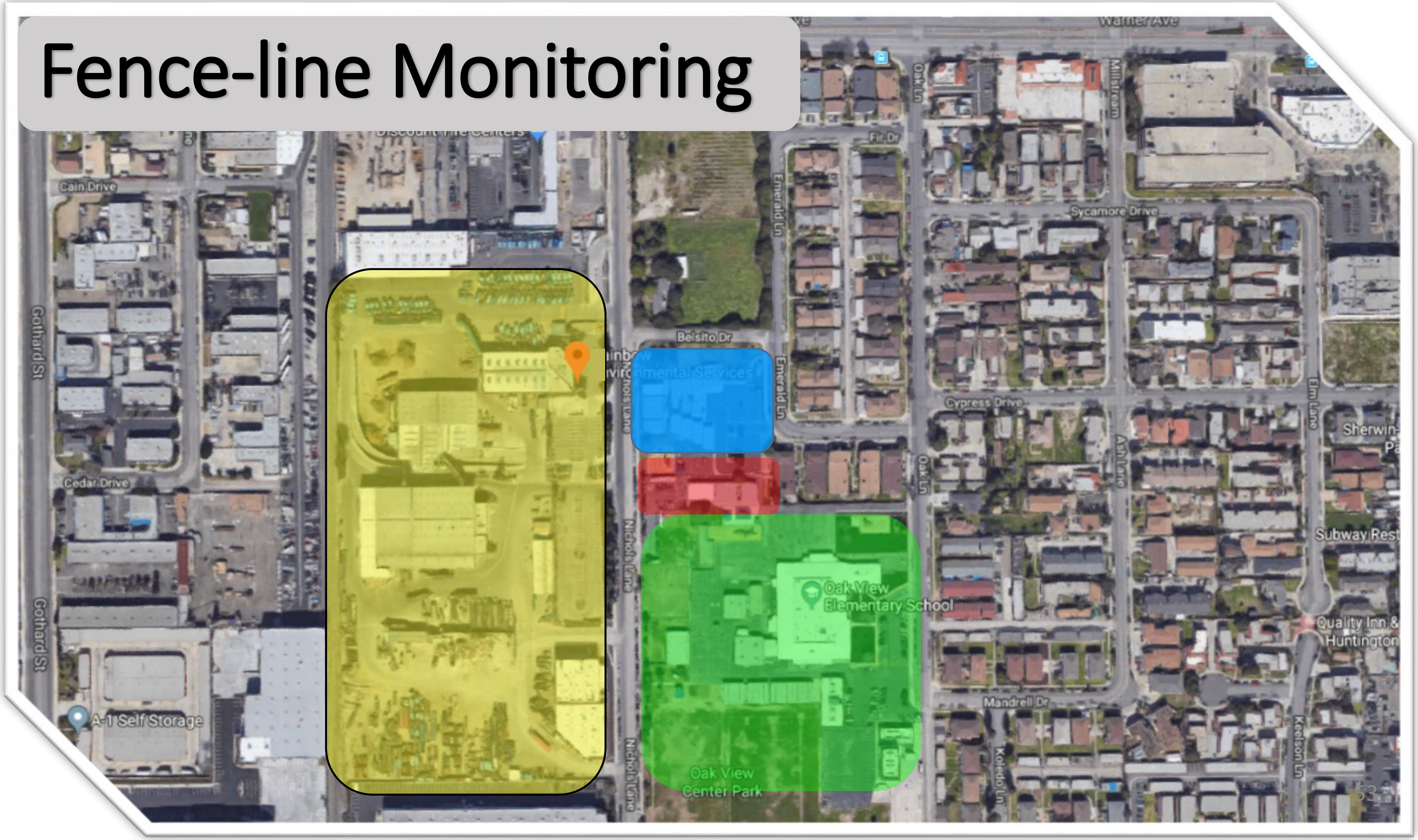
14 Acre Waste Transfer Facility

Pre School Campus

Head start Academy

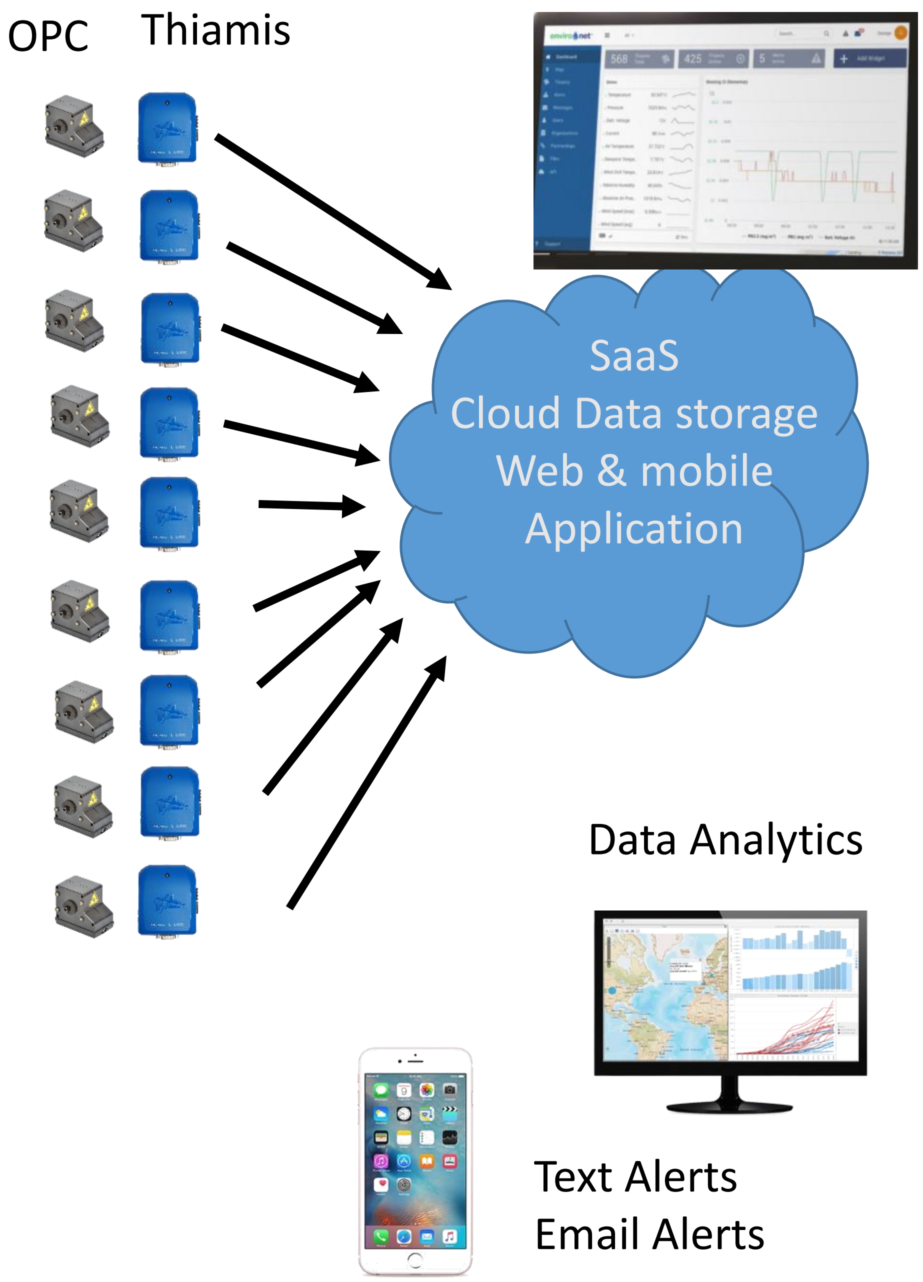
Elementary School





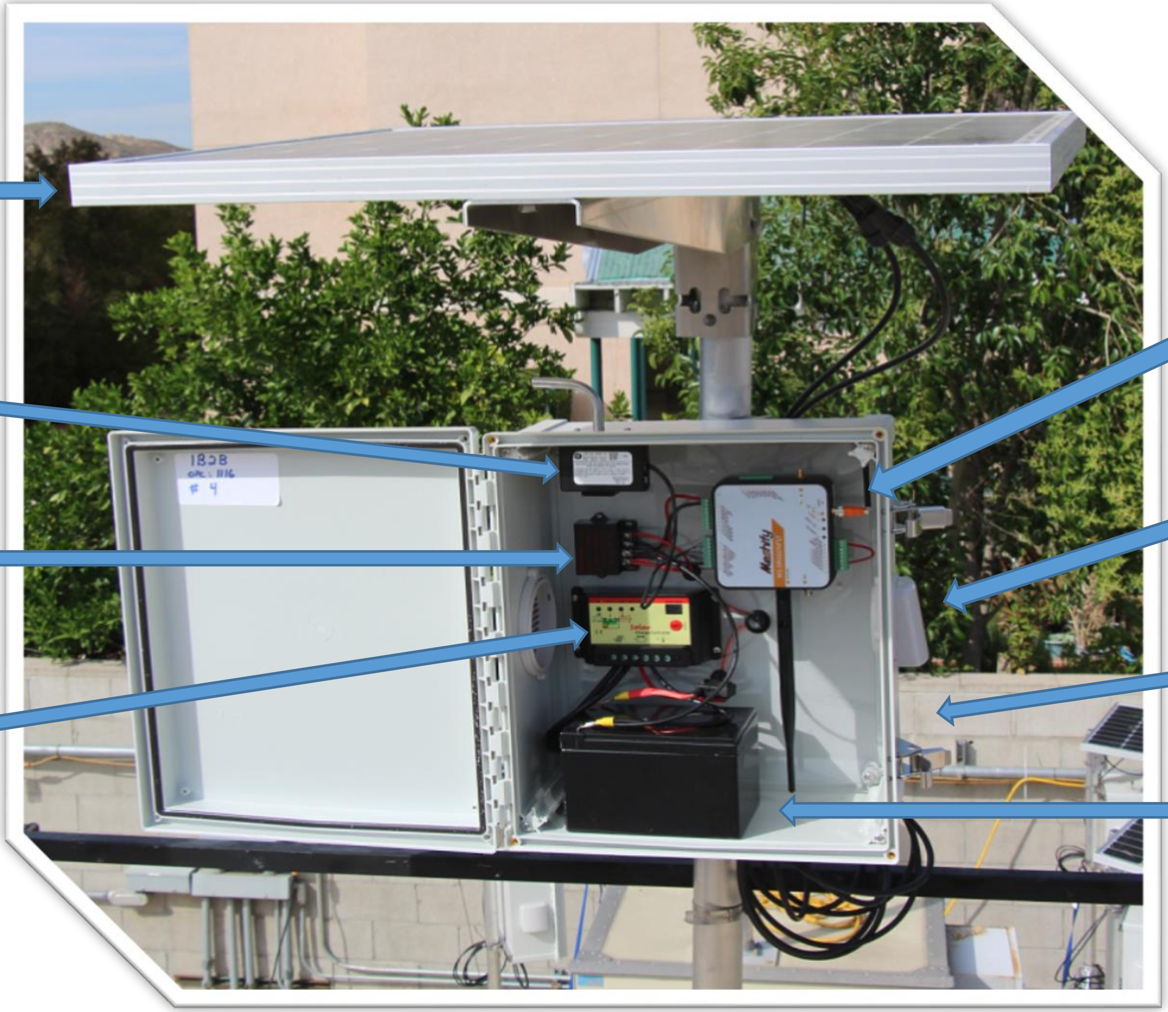
Fence-line Monitoring

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



AQ-SPEC
Air Quality Sensor Performance Evaluation Center

$1500 / device



Solar Panel & pole mount
~ $120

Alphasense OPC
~ $400

Power Converter
~ $10

Charge Controller
~ $20

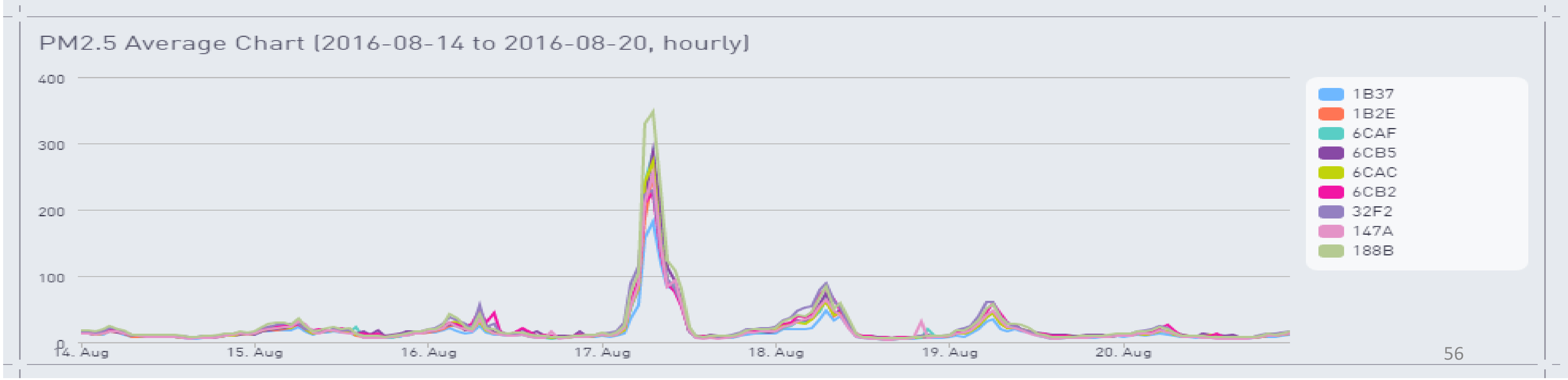
IOT Connectivity Hardware
~ $750

Box Vents
~ $10

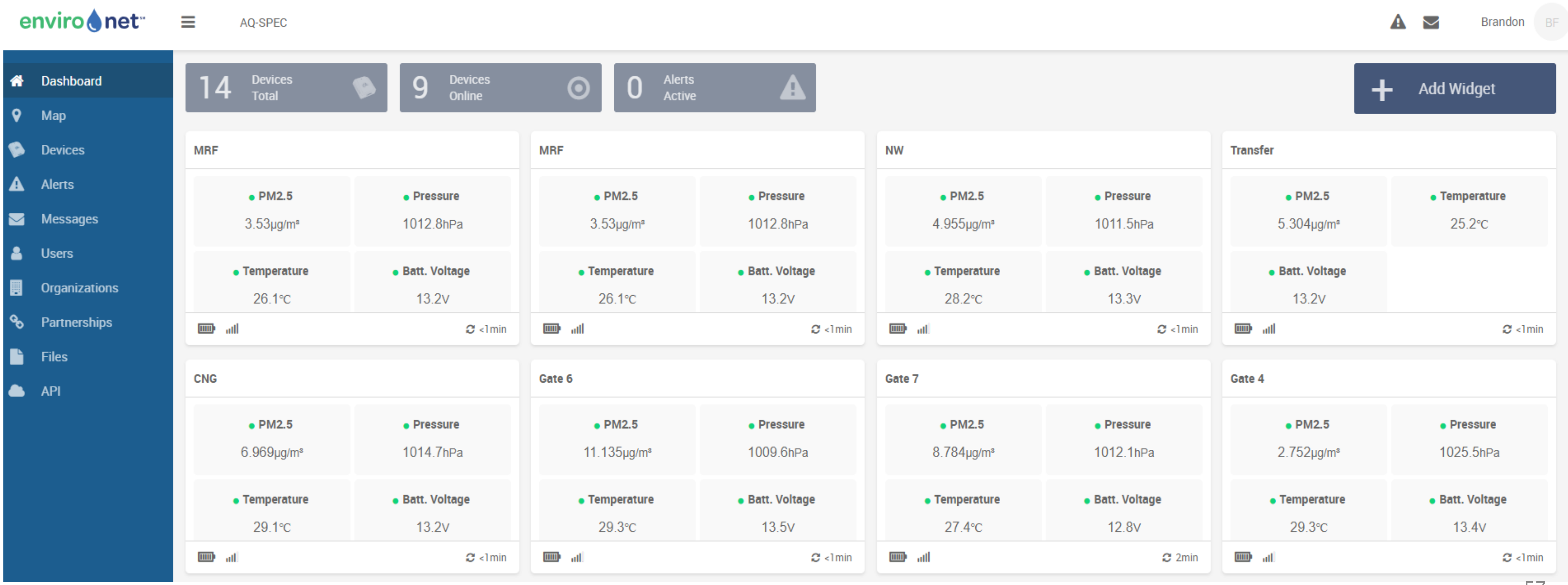
Enclosure with mounting kit
~ $70

12V Battery
~ ~~$30~~ $130

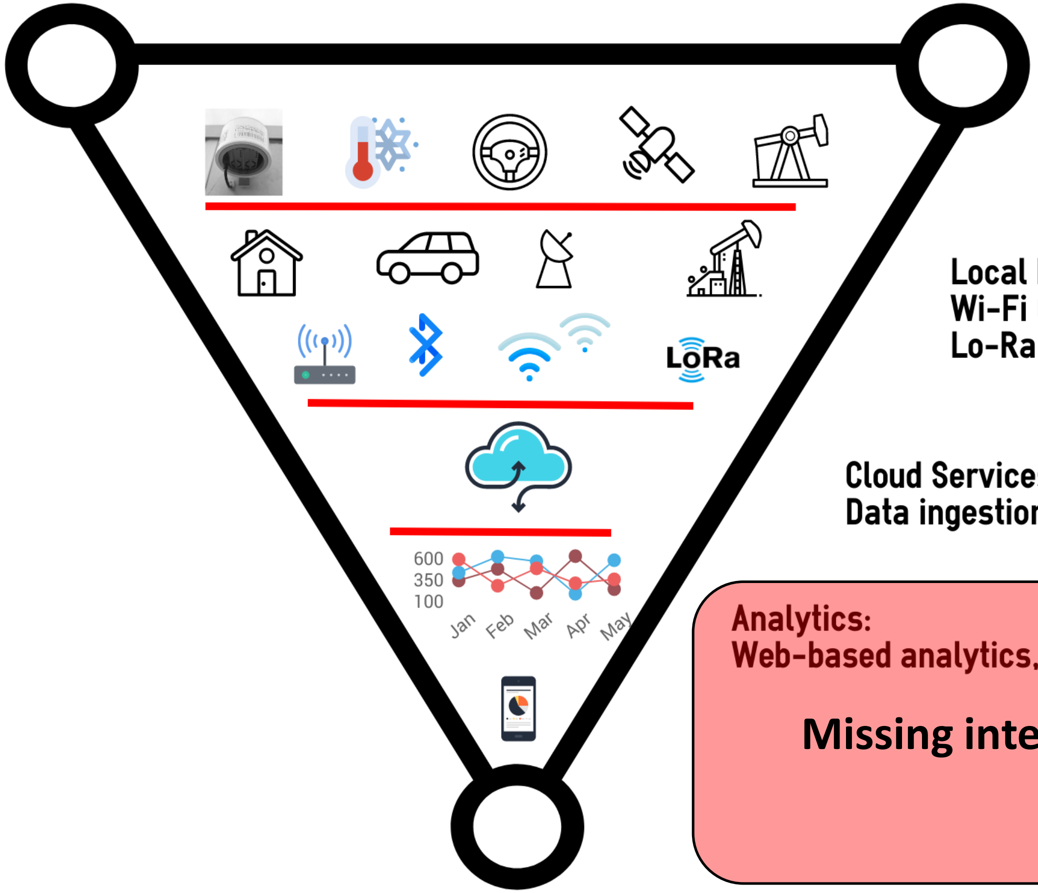

Washington Drive
Elk Cir
Woodlake Dr
Warner Ave
Gothard St
Palmdale Lane
Cain Drive
Cedar Drive
Nichols Lane
Belsito Dr
Emerald Ln
Fir Dr
Oak Ln
Millstream
Sycamore Drive
Cypress Drive
Ash Lane
188B
1B37
6CAC
6CAF
1B2E
147A
HEATMAPS
FROM
8/16/2016, 12:20 pm
TO
8/18/2016, 12:20 pm
CHANNEL
PM10


PM2.5 Average Chart [2016-08-14 to 2016-08-20, hourly]
400
300
200
100
0
14. Aug
15. Aug
16. Aug
17. Aug
18. Aug
19. Aug
20. Aug
1B37
1B2E
6CAF
6CB5
6CAC
6CB2
32F2
147A
188B

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:
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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

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

SCAQMD Sensor projects

Fence-line monitoring	**Regional monitoring network**	Community monitoring	Future monitoring projects
9 PM sensors	**~ 100 AQY nodes**	STAR Grant	Hotspot identification
	Measures	~ 390 PM sensors in 14 communities	
IoT vendor platform	**• O_3, NO_2, & PM**		Mobile monitoring
Cellular to SaaS	**Cellular to PaaS**	Wi-Fi connected	AB617 community monitoring
		Data sent to:	
API Access	**API access**	• Purple Air Map • AQMD Azure	
			SCAQMD Rule 1180 implementation

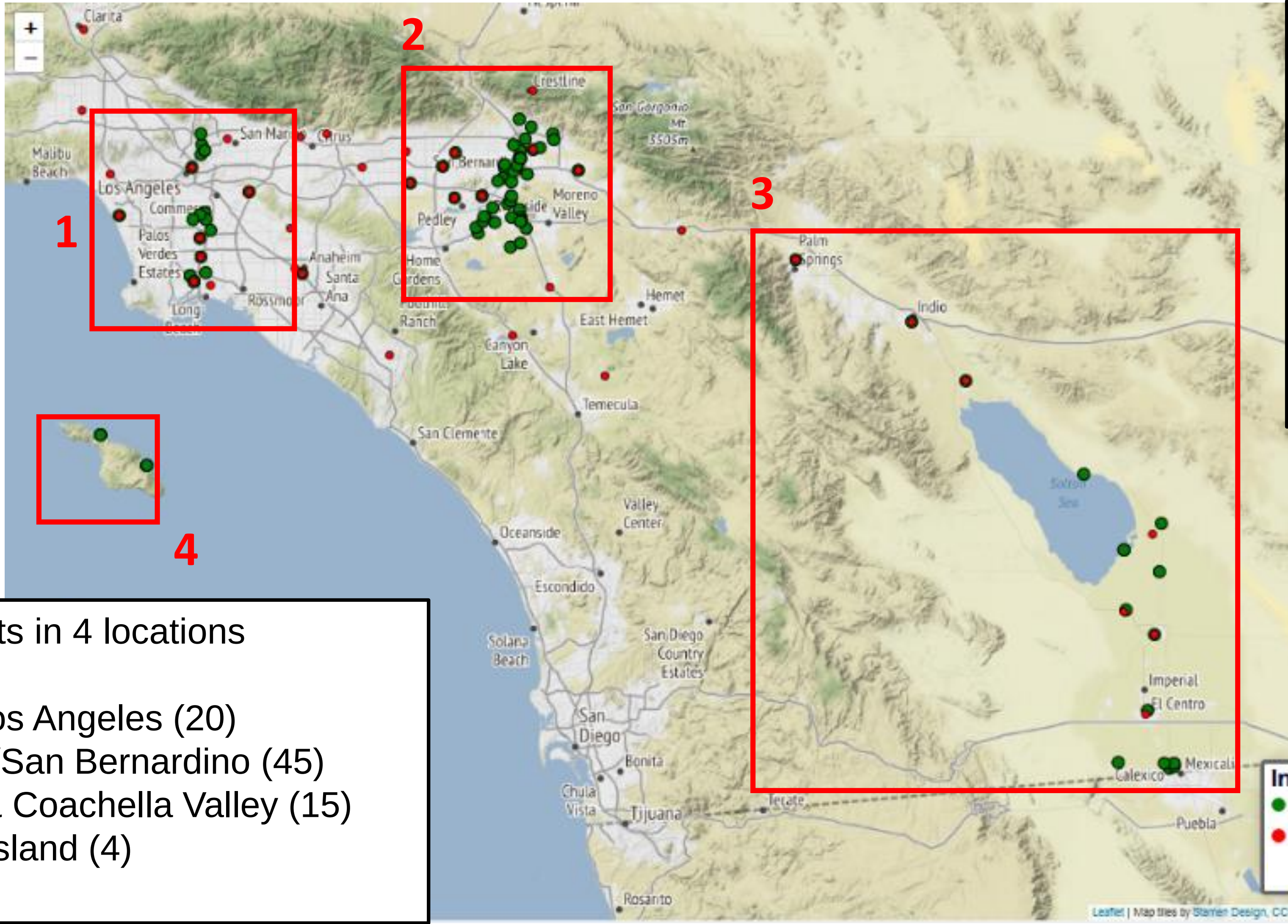
Regional Monitoring Network Aims

- 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

South Coast AQMD



Aeroqual AQY

Multi-pollutant Air Quality Monitor

- Measures: O3, NO2, PM2.5, PM10, T/RH/DP
- Cellular communication to Aeroqual Cloud server allowing real-time data acquisition (and on-board storage)
- Powered via mains to 12V step down transformer
- Small size (180x180x180mm)

92 instruments in 4 locations

1 - Central Los Angeles (20)
2 - Riverside/San Bernardino (45)
3 - Imperial & Coachella Valley (15)
4 - Catalina Island (4)

South Coast AQMD

AQ-SPEC

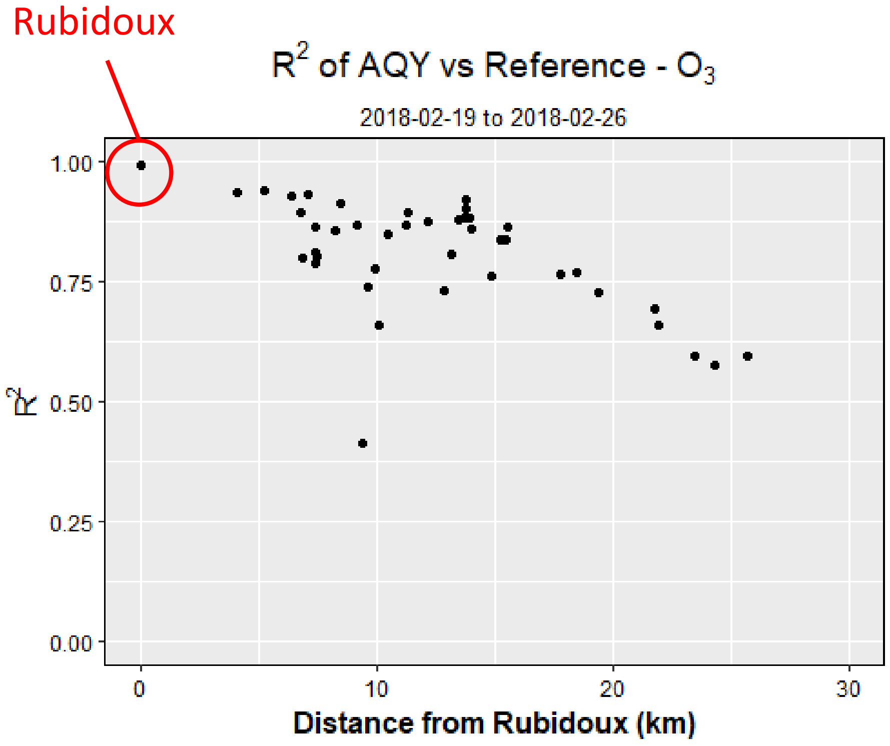
Air Quality Sensor Performance Evaluation Center

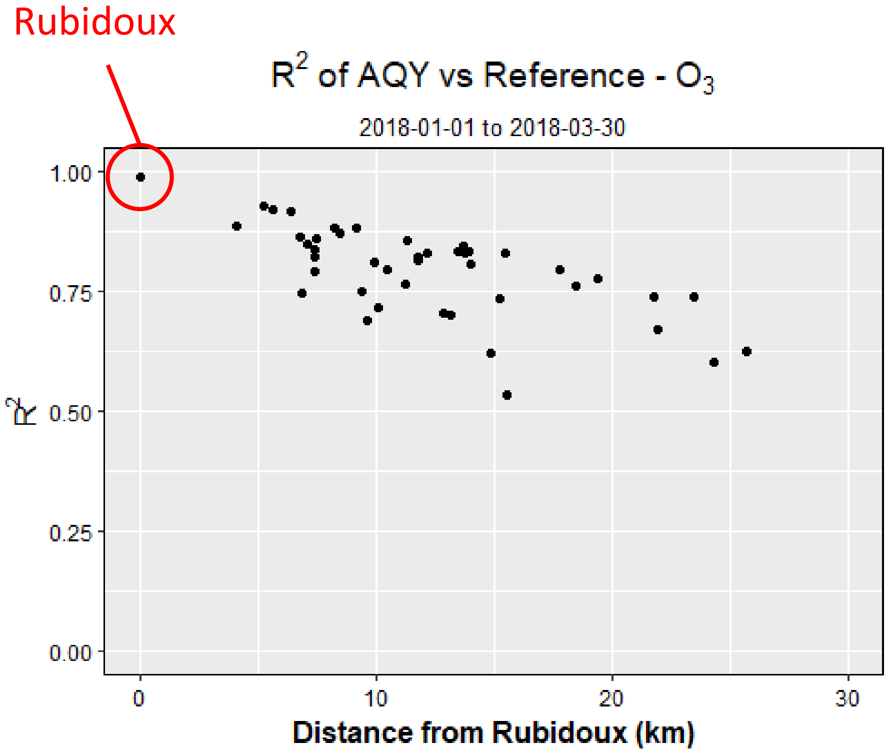






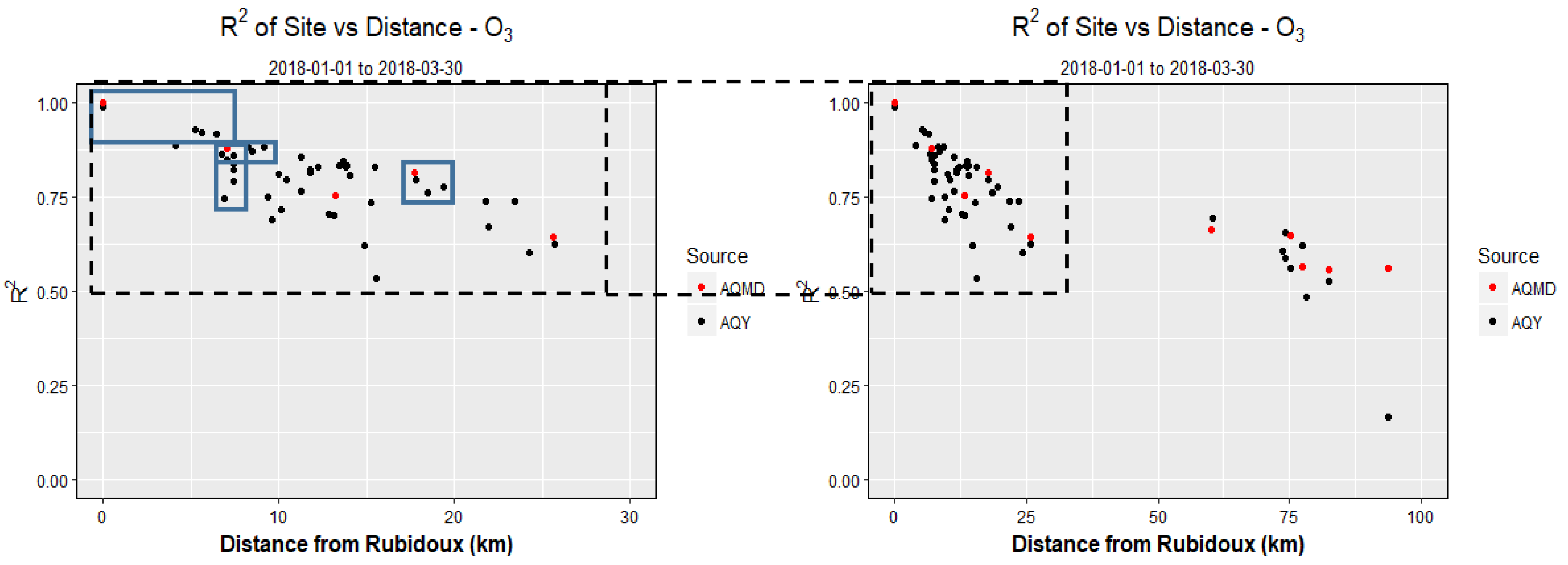
R^2 (AQY vs Reference) vs Distance: Ozone





- A one week ‘snapshot’ is similar to the 3 month period

R^2 (AQY vs Reference) vs Distance: Ozone



- 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

South Coast AQMD

AQ-SPEC

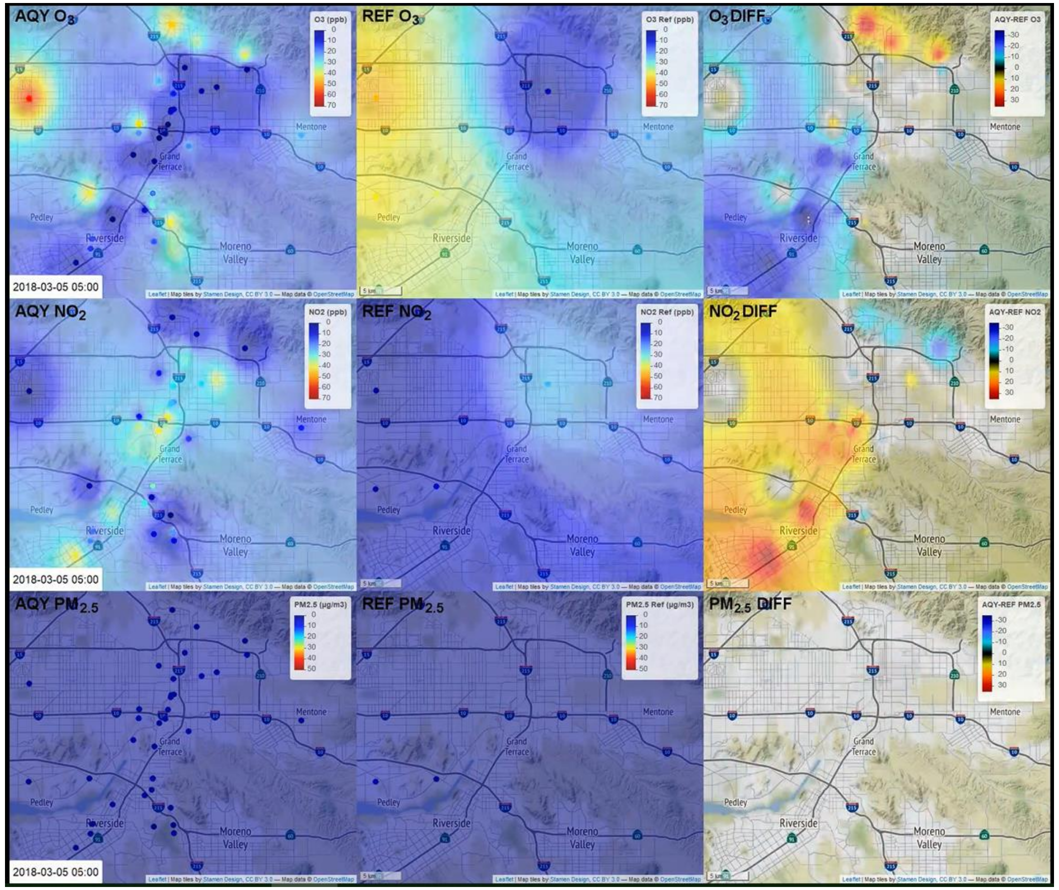
Air Quality Sensor Performance Evaluation Center

AQY | Reference | Difference

Ozone

Nitrogen Dioxide

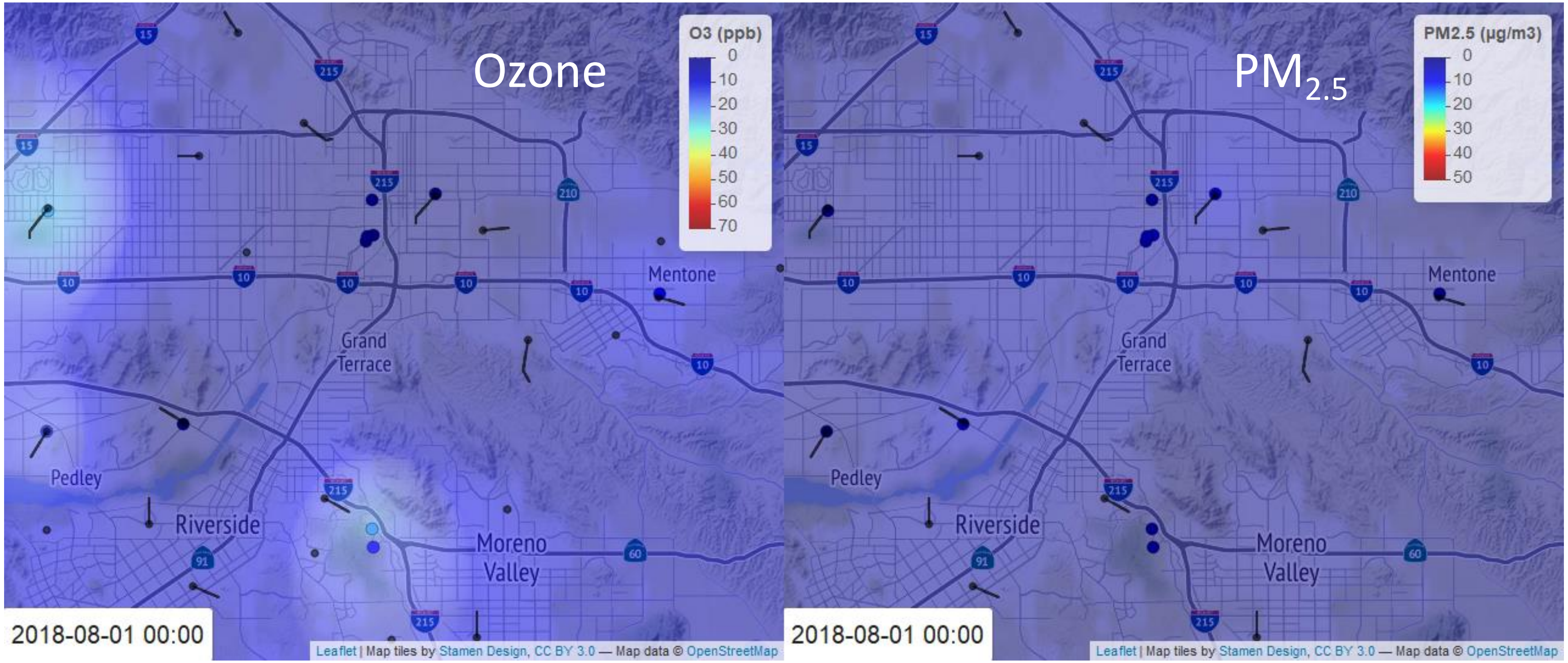
$PM_{2.5}$



- Higher granularity for maps obtained using sensor data
- Elevated NO_2 along the freeway
- $PM_{2.5}$ is more homogeneously distributed throughout the Basin

*Inverse distance weighted interpolation

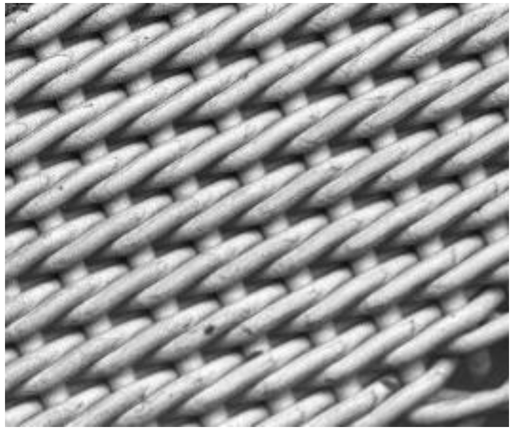
Aeroqual AQY - Heat map animations



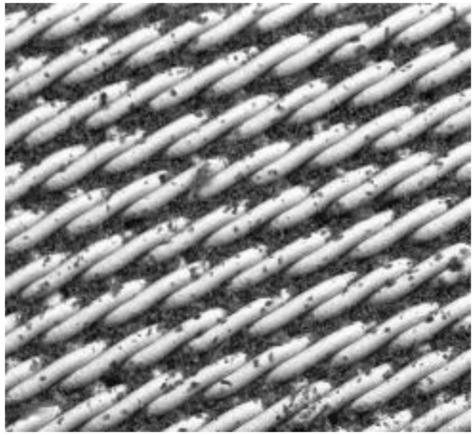
Performance over time: The project has shown PM accumulates on the O_3 sensor inlet mesh over time reducing flow and sensitivity

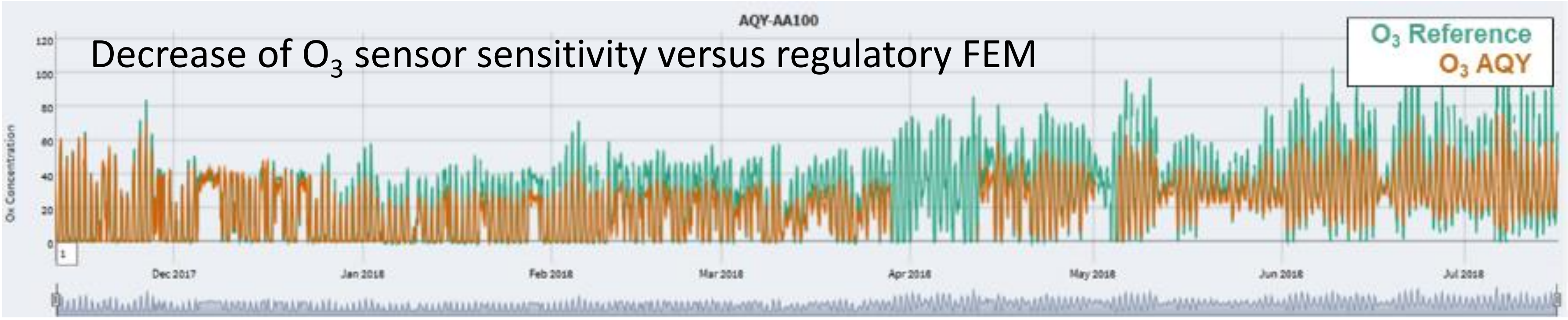
O_3 sensor inlet

mesh at start



mesh after 6 months





Decrease of O_3 sensor sensitivity versus regulatory FEM

Regional Network Review

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

SCAQMD Sensor projects

Fence-line monitoring	Regional Monitoring Network	**Community monitoring**	Future monitoring projects
9 PM sensors IoT vendor platform Cellular to SaaS API Access	~ 100 AQY nodes Measures • O_3, NO_2, & PM Cellular to PaaS API access	**STAR Grant** **~ 390 PM sensors in 14 communities** **Wi-Fi connected** **Data sent to:** • **Purple Air Map** • **AQMD Azure**	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

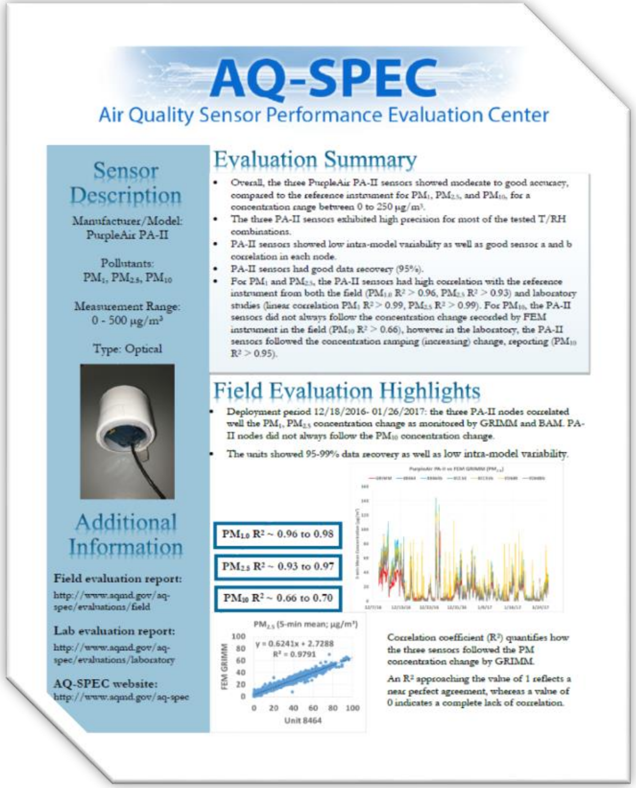
AQ-SPEC

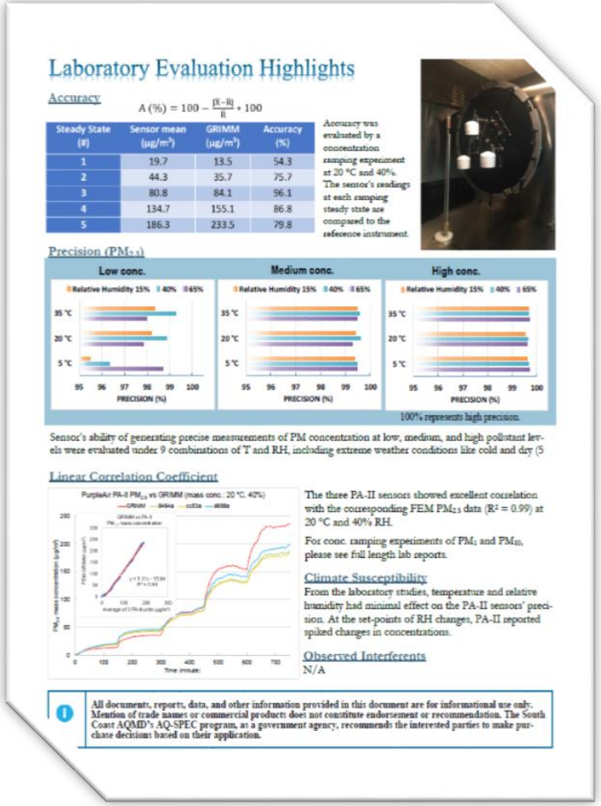
South Coast AQMD

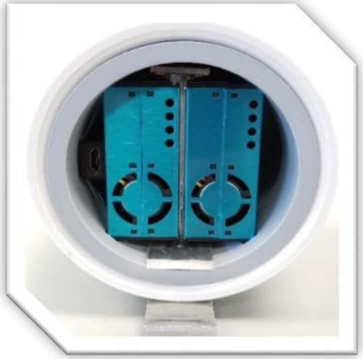
Air Quality Sensor Performance Evaluation Center

PM Sensors

Sensor Image	Manufacturer (Model)	Type	Pollutant(s)	Approx. Cost (USD)	*Field R^2	*Lab R^2	Summary Report
	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-I-Indoor)	Optical	$PM_{1.0}$, $PM_{2.5}$ & PM_{10}	~\$180	$PM_{2.5}$: R^2 ~ 0.75 PM_{10}: R^2 ~ 0.36 to 0.46		
	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)
	SainSmart (Pure Morning P3)	Optical	$PM_{2.5}$	~\$170	R^2 ~ 0.73	R^2 ~ 0.99	PDF (1,186 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	R^2 ~ 0.99	PDF (5,647 KB)
	uHoo	Optical	$PM_{2.5}$	~\$300	R^2 ~ 0.0		





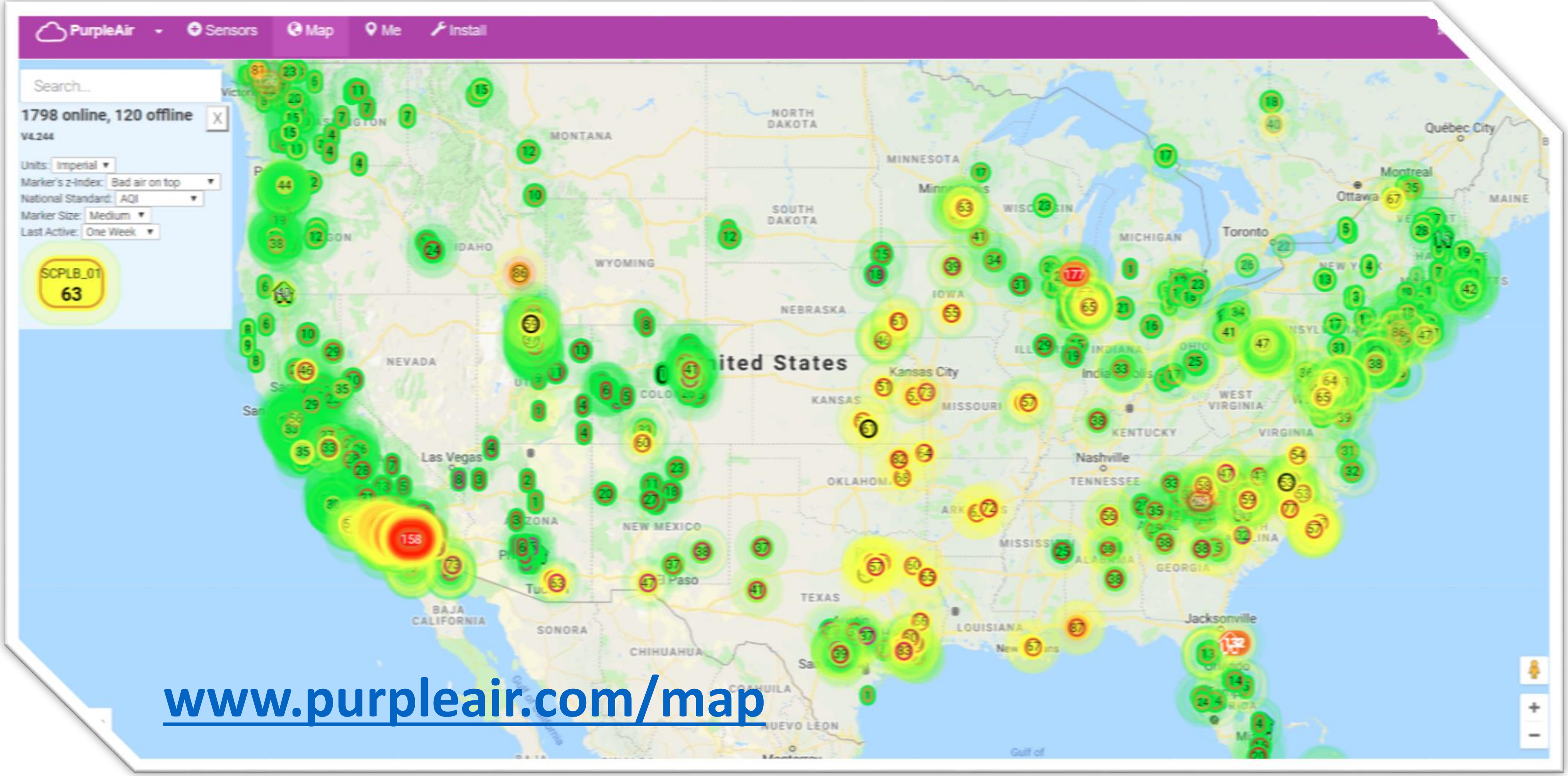


www.aqmd.gov/aq-spec

South Coast AQMD

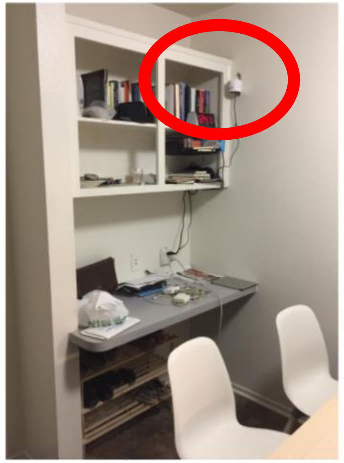
AQ-SPEC

Air Quality Sensor Performance Evaluation Center

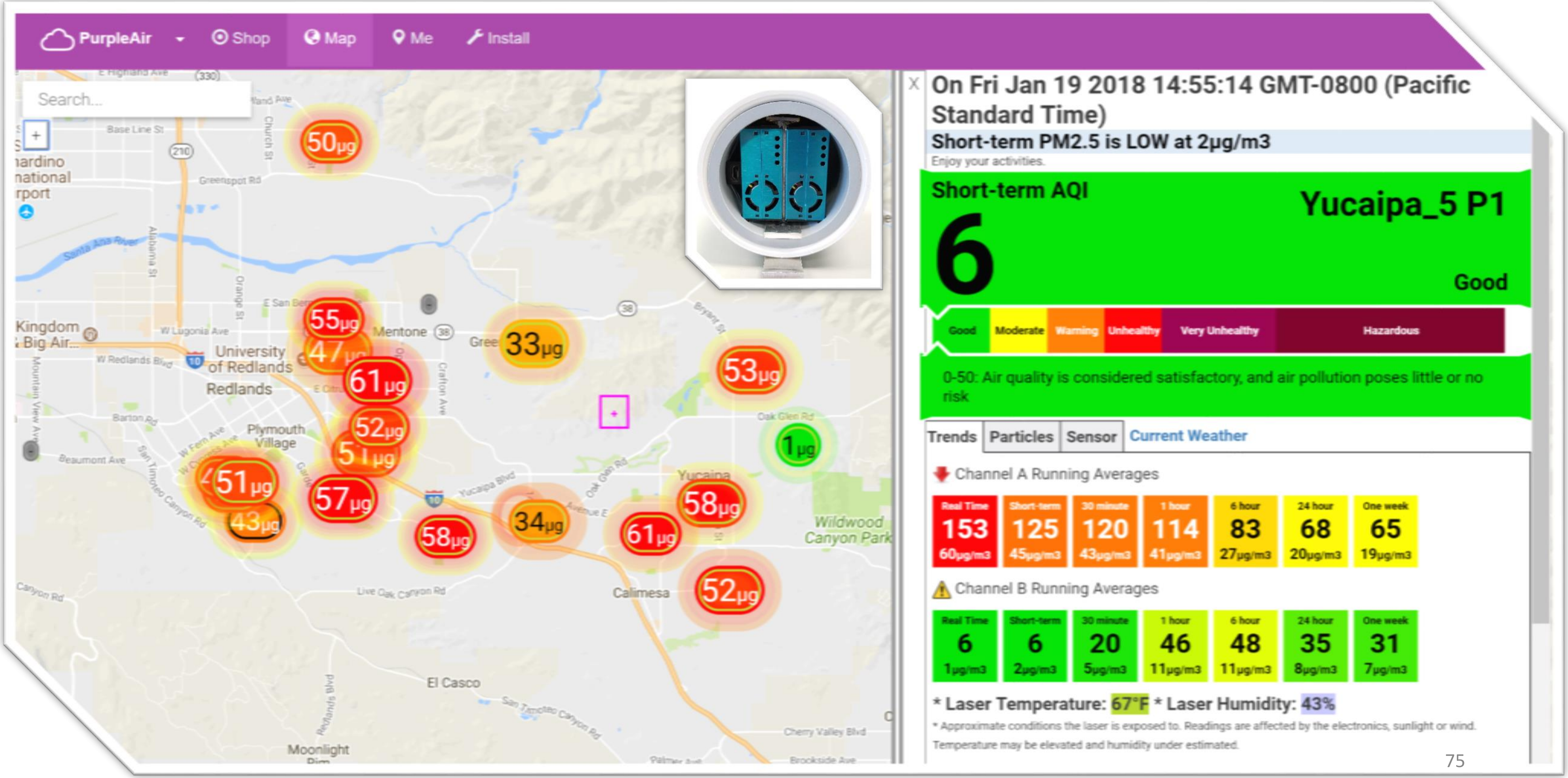


www.purpleair.com/map

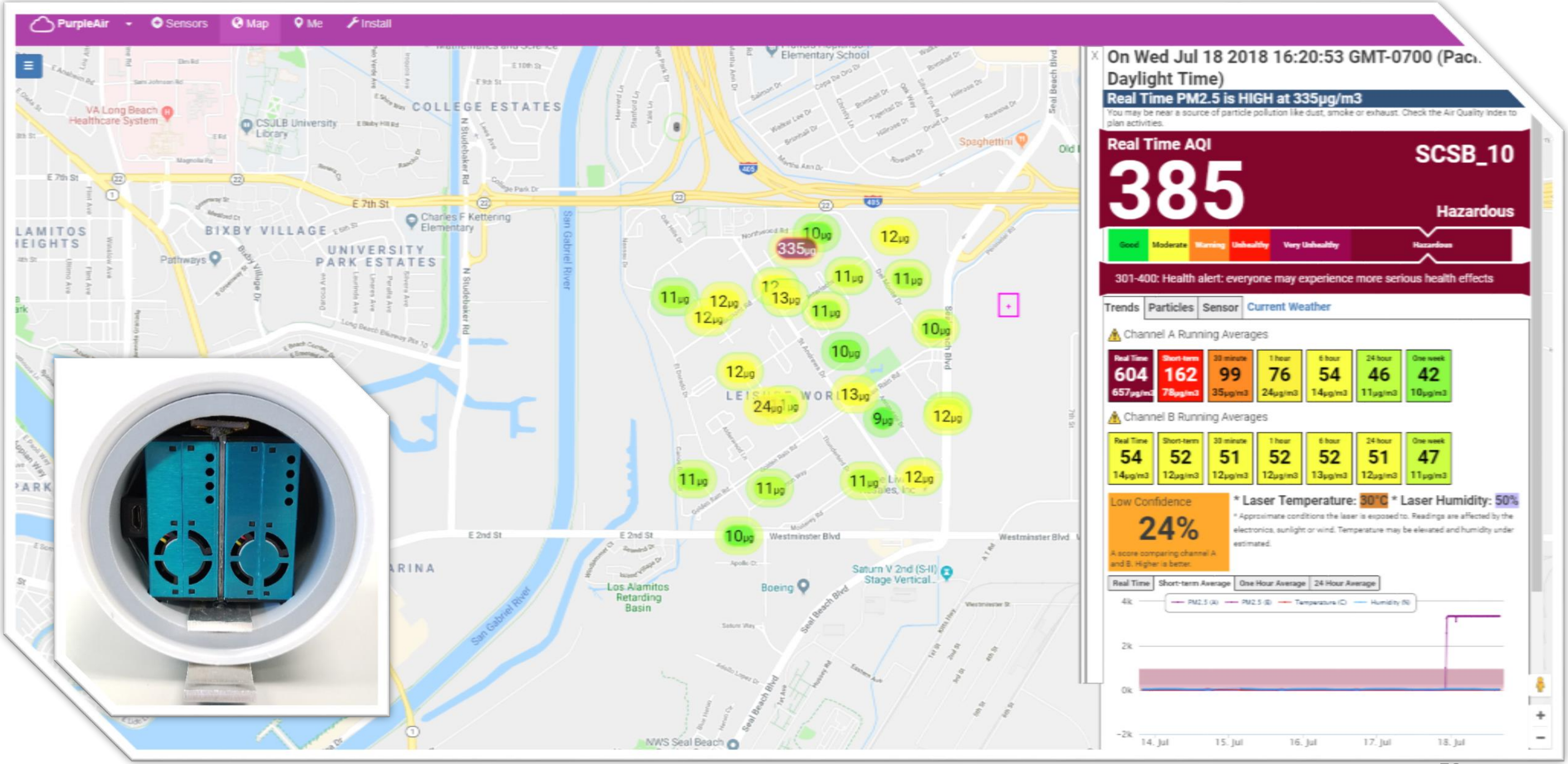
Community Siting



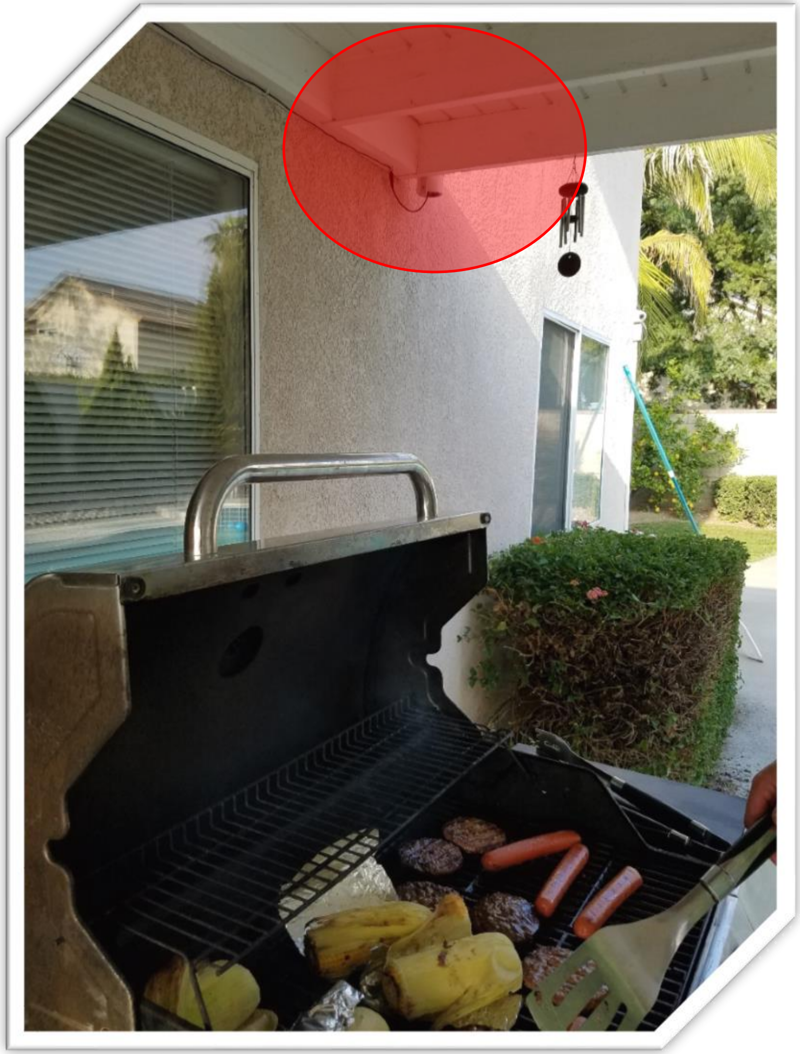
End User Interface

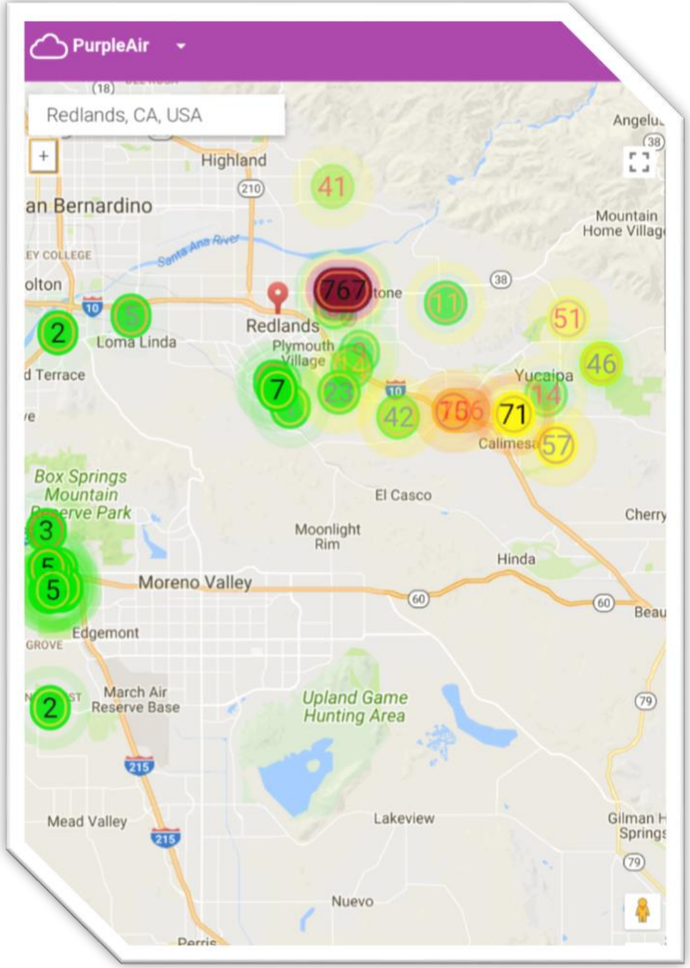


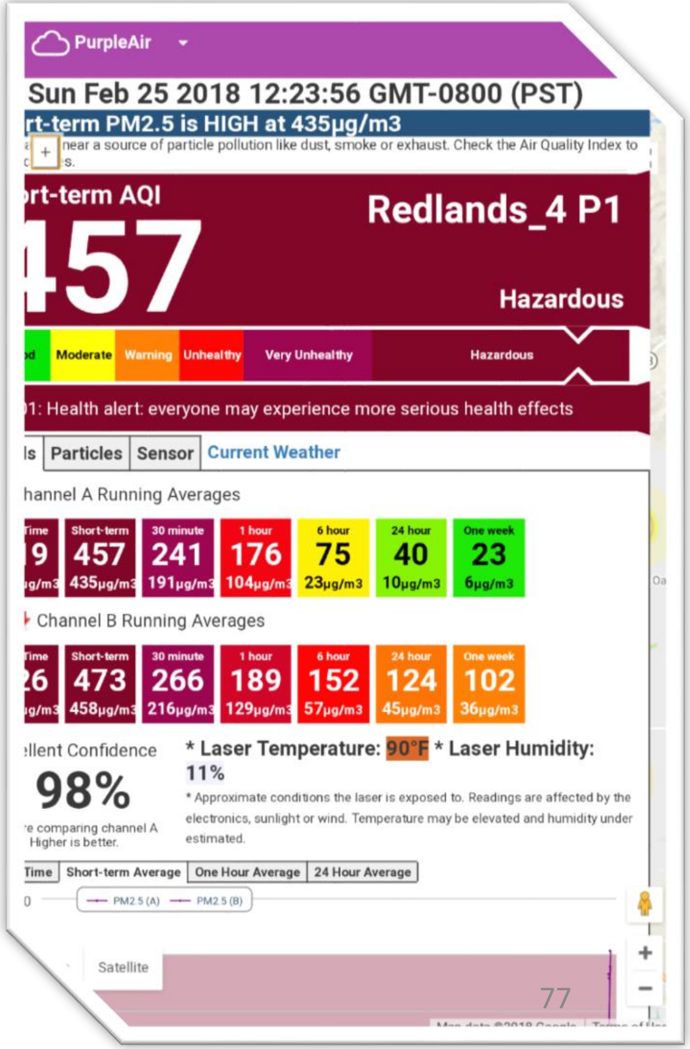
End User Interface



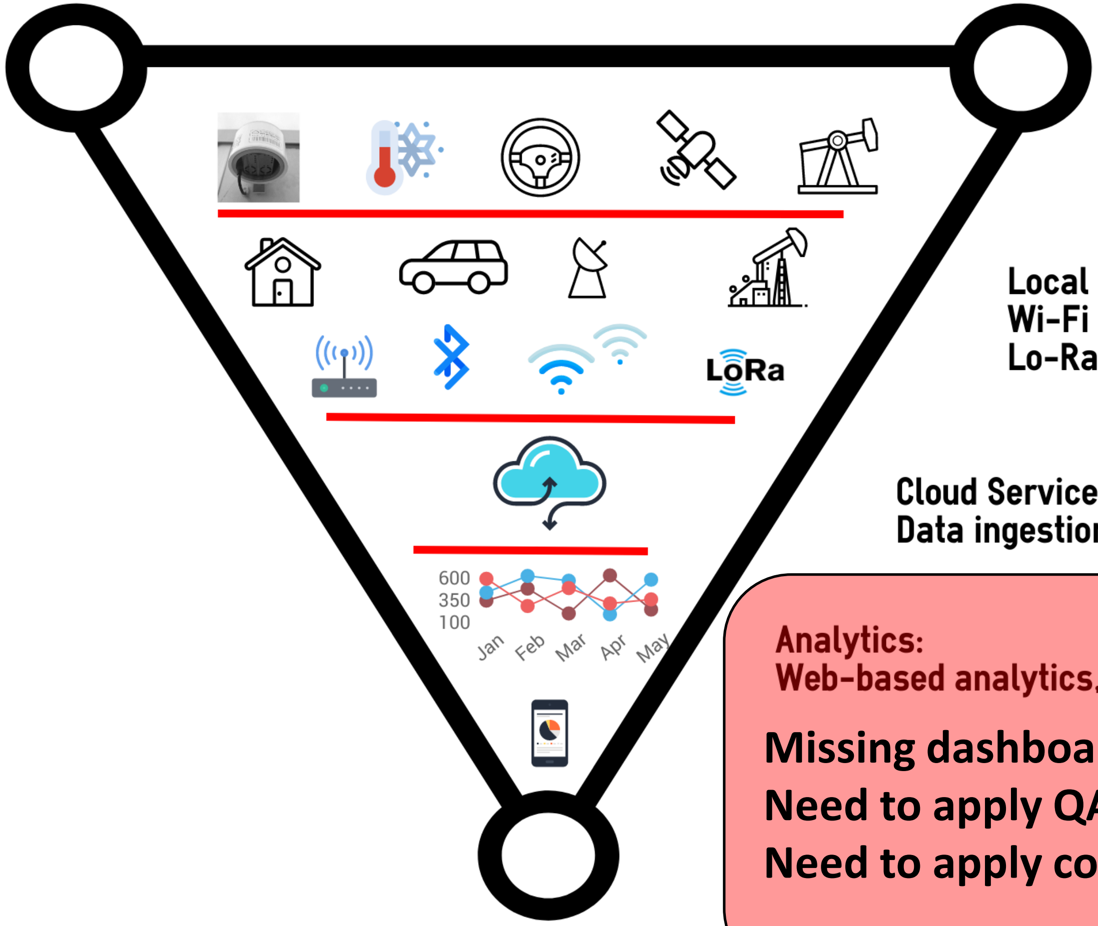
Hyper-local effects







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 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

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

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

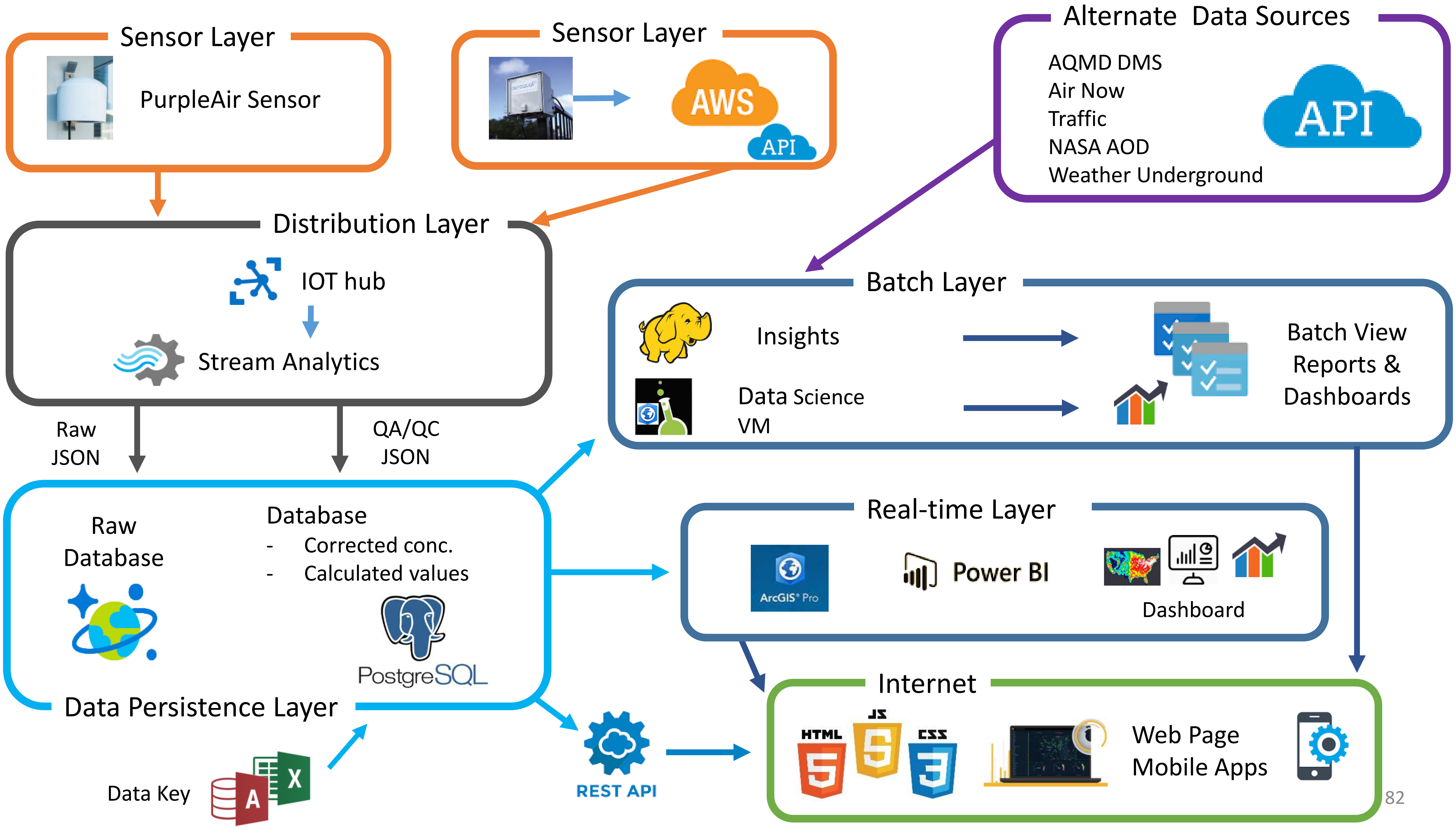
Cloud Platform requirements:

- 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

Draft Cloud Architecture



Thank you - Questions?

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