AQ-SPEC

Air Quality Sensor Performance Evaluation Center

AQ-SPEC:

Sensor Performance Evaluations

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Davis, CA - 06/05/19

Primary Quality Assurance Organization Training

OUTLINE

- Background
- AQ-SPEC
  - Lab
  - Field
- Field PM Sensor Results

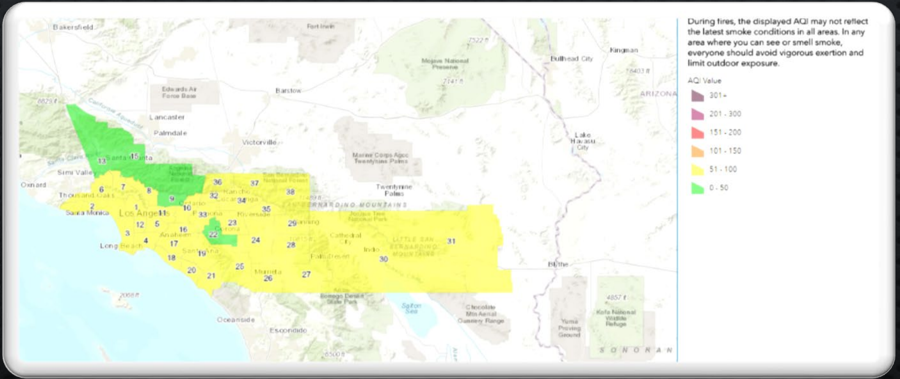
HISTORICAL AMBIENT AIR MONITORING

Clean Air Act (CAA)

- Approved Federal Reference (FRM) and Equivalent Methods (FEM)
- Regional Networks = Determine Regional Attainment of NAAQS

Recent legislation

- CA Assembly Bill AB617 (Passed)
- House Bill 1284 - Crowd Sourcing of Environmental Data Act of 2019 (Introduced)



Low-cost Sensors

- Technical advancements
- Cost Reductions
  - Hardware
  - Connectivity
  - Cloud computing
- Rapidly gaining attention

Potential for ambient air Monitoring

- Fence-line, community, hot-spot identification, mobile monitoring, personal exposure, science education

1800-1980

2011

2012

2013: EPA Next Generation Air Sensors Conference

2014 South Coast AQMD AQ-SPEC Air Quality Sensor Performance Evaluation Center

2015-2019: New Start-ups

2016-2019: Development of sensor networks

HOW CAN SENSORS FIT IN?

Public Health

- What are the concentrations?
- What is the spatial-temporal variability?

Inform Mitigation Efforts

- What are the sources and their relative contribution?
- How much is locally produced versus transported over long distances?

Inform and Empower the public

- Collect data applicable to personal exposure
- Modify habits to reduce exposure

South Coast AQMD

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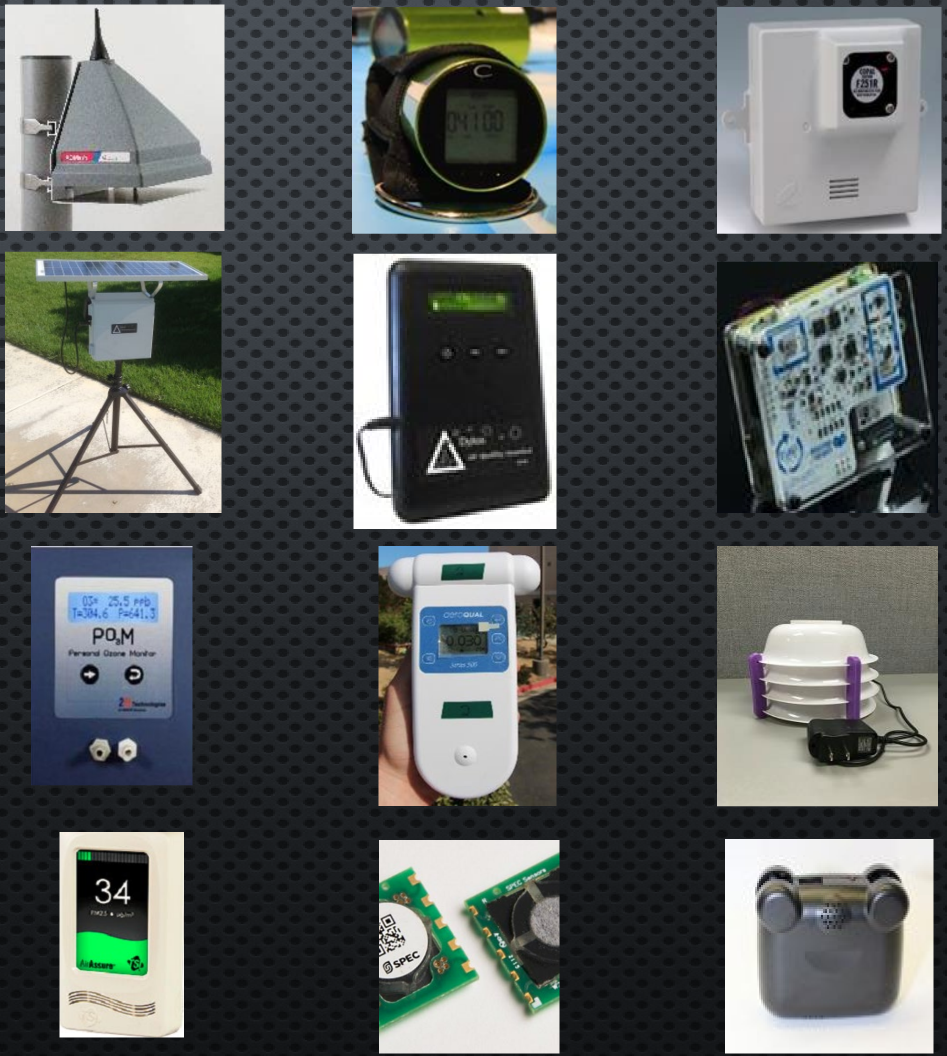
Air Quality Sensor Performance Evaluation Center

- Established in July 2014
  - Over $600,000 initial investment
- 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
  - Sensitivity at ambient levels
  - Continuous operation for two months
  - Retrievable data
  - Low-cost…?



FIELD PERFORMANCE EVALUATION

- Sensors tested in triplicates
- Two month deployment (various time intervals, random)
- South Coast AQMD Riverside-Rubidoux Air Monitoring Station
  - Fully instrumented
  - Inland site
  - 1 km from CA SR 60
  - Impacted by regional aerosol formation

LABORATORY PERFORMANCE EVALUATION

- ✓ 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

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LABORATORY EVALUATION (HISTORY AND WHAT'S NEXT)

Received Chamber Summer 2015

- AQ-SPEC staff worked closely with the chamber system integrator to customize the system to the anticipated needs and requirements (12 months)
- AQ-SPEC staff developed Methods for Aerosol and Gas testing atmospheres in-house (6 months)

PAPAPOSTOLOU V, ZHANG H, FEENSTRA B, AND POLIDORI A. DEVELOPMENT OF AN ENVIRONMENTAL CHAMBER FOR EVALUATING THE PERFORMANCE OF LOW-COST AIR QUALITY SENSORS UNDER CONTROLLED CONDITIONS. *ATMOSPHERIC ENVIRONMENT*, 171: 82-90, 2017

State-of-the-art system

Systematically evaluate performance of sensors

Produce stable and reproducible PM and Gas test atmospheres

Produce a wide range of known target/interferent pollutant concentrations, temperature and relative humidity conditions

Sensor data communication options

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EVALUATION PARAMETERS:

- Intra-model variability
- Accuracy
- Precision
- Coefficient of Determination (R^2)
- Data Recovery
- Climate Susceptibility
- Interferent (monodisperse aerosols)

16 Lab Evaluations Completed

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

Challenges:

- Stability of PM_{10} atmospheres
  - Due to nature of test particles
- Sensor performance degradation experiments
- Temperature and RH cycling tests for long periods of time

- Developing:
  - ASTM D22.05 Testing Protocol
    - Low-Cost Indoor Air Quality sensors for measuring CO_2 and $PM_{2.5}$
  - VOC Sensor Testing Protocol
    - Total VOC, speciated VOC
- New contract in place for a second chamber system (delivered end of 2019) to accommodate testing of 20+ sensors simultaneously, aging/vibration/wind effects/rapid climatic changes experiments:
    - Development of sensor performance standards
    - AQ-SPEC Sensor Library program
    - Testing protocol for sensors conducting mobile ambient air measurements

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PM SENSORS – FIELD EVALUATION RESULTS

In Review: Feenstra, et al. 2019. Performance Evaluation of Twelve Low-cost PM2.5 Sensors at an Ambient Air Monitoring Site, *Atmospheric Environment*

Performance Evaluation Parameters

- Intra-model variability
- Accuracy
- Measurement Error
- Impact of local conditions

Data Filters to Improve Inter and Intra-model comparison

- $PM_{2.5}$ > 50 µg/m^3 removed
- If reference or any of 3 sensors missing a 1-hr value, data row removed from analysis

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PERFORMANCE EVALUATION OF TWELVE LOW-COST $PM_{2.5}$ SENSORS AT AN AMBIENT AIR MONITORING SITE

Manufacturer	Model	Pollutants Measured	Time Resolution	Cost
Aeroqual	AQY	$PM_{2.5}$, O_3, NO_2	1-min	$3,000
Airboxlab	Foobot	$PM_{2.5}$, CO_2, VOC	5-min	$200
Alphasense	OPC-N2	$PM_{2.5}$	< 1-min	$450
HabitatMap	Air Beam 1	$PM_{2.5}$	1-min	$200
Hanvon	N1	$PM_{2.5}$, HCHO	1-min	$200
Kaiterra	LaserEgg	$PM_{2.5}$	< 1-min	$200
PurpleAir	PA-II	$PM_{2.5}$, PM_{10}, $PM_{1.0}$	< 1-min	$230
SainSmart	Pure Morning P3	$PM_{2.5}$, CO_2, HCHO	< 1-min	$170
Shinyei	PM Evaluation Kit	$PM_{2.5}$	1-min	$1,000
TSI	AirAssure	$PM_{2.5}$	5-min	$1,000
Uhoo	uhoo	$PM_{2.5}$, O_3, NO_2, CO, CO_2, TVOC	1-min	$300
IQAir	AirVisual Pro	$PM_{2.5}$, CO_2,	< 1-min	$270

BIAS ERROR CALCULATIONS

$$\text{Mean Bias Error (MBE)} = \frac{1}{n}\sum_{i=1}^{n}(X_i - X_t)$$

$$\text{Mean Absolute Error (MAE)} = \frac{1}{n}\sum_{i=1}^{n}|(X_i - X_t)|$$

Where,

X_i is the 1-hr average measurement by the low-cost sensor

X_t is the 1-hr average measurement provided by the reference

n is the number of 1-hr time-matched data pairs

REGRESSION AND MEASUREMENT ERROR

Aeroqual
- Intercept and Bias

Hanvon & Purple Air & Sainsmart
- Over-estimate

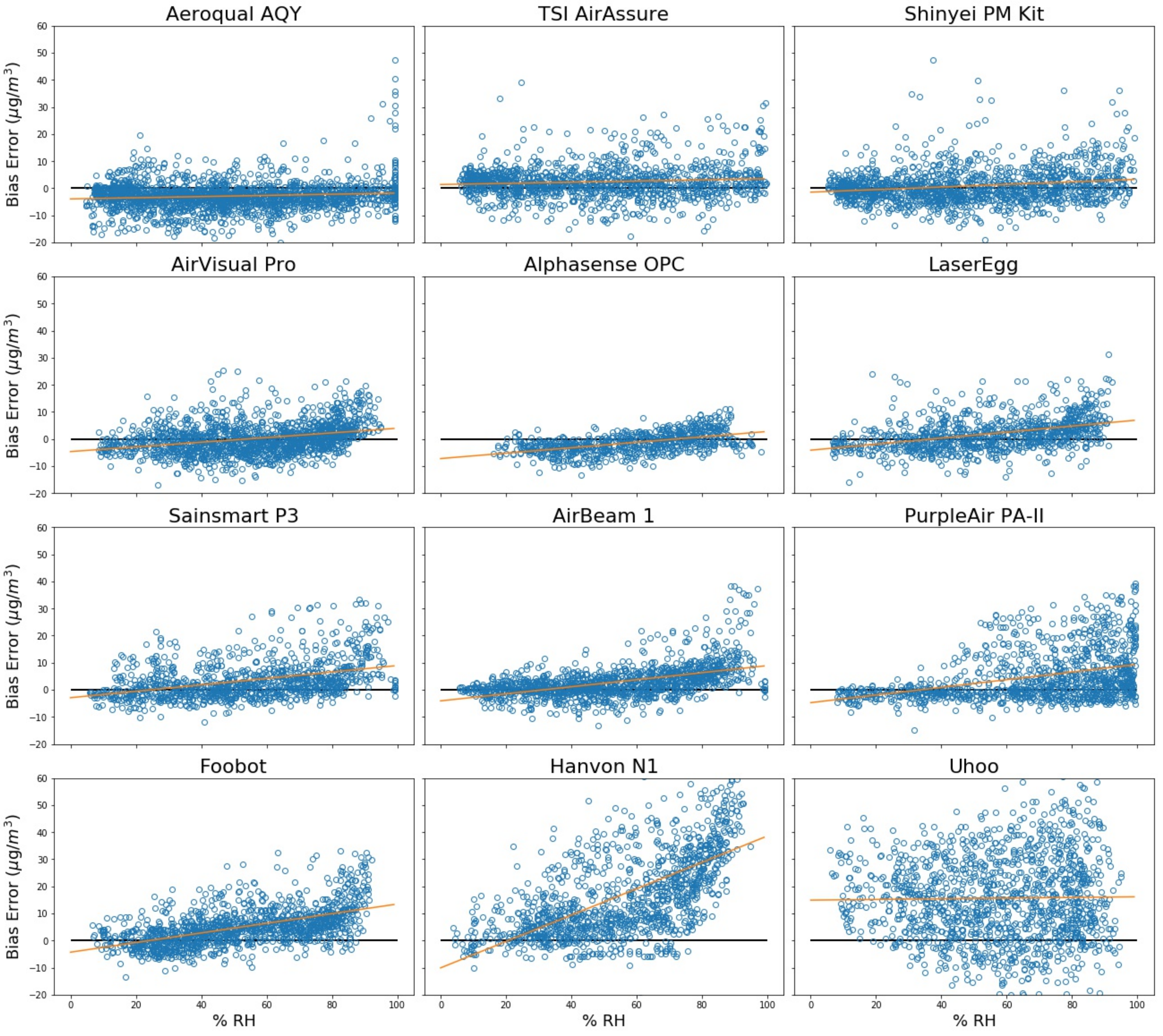
Kaiterra Laser Egg
- Importance of R^2

Uhoo
- Poor performance

			Slope		Intercept		Measurement Error (μg/m³)	
Sensor	#	R^2	Slope	95% CI	Intercept	95% CI	MBE	MAE
Aeroqual AQY	1	0.78	0.99	0.02	-2.75	0.39	-2.9	4.5
	2	0.79	1.01	0.02	-3.08	0.38	-3.0	4.7
	3	0.79	0.94	0.02	-2.63	0.35	-3.4	4.6
Airboxlab Foobot	1	0.57	1.32	0.06	0.28	1.00	5.0	6.4
	2	0.54	1.08	0.05	1.35	0.86	2.6	4.7
	3	0.54	1.29	0.07	4.89	1.03	9.2	9.5
Alphasense OPC	1	0.67	0.78	0.04	2.08	0.67	-1.3	3.3
	2	0.38	0.57	0.05	1.18	0.90	-5.5	6.5
	3	0.40	0.67	0.06	1.03	1.01	-4.2	5.9
HabitatMap Air Beam 1	1	0.59	1.08	0.05	2.03	0.63	2.9	4.4
	2	0.57	1.47	0.07	0.46	0.90	5.7	6.5
	3	0.57	1.66	0.08	-0.62	1.01	6.8	7.5
Hanvon N1	1	0.56	2.13	0.10	0.91	1.71	17.4	18.1
	2	0.54	1.91	0.10	2.69	1.59	15.9	16.3
	3	0.58	1.73	0.08	2.39	1.34	13.1	13.5
Kaiterra LaserEgg	1	0.57	1.15	0.06	-0.08	0.95	2.0	4.7
	2	0.56	1.02	0.06	-0.40	0.85	-0.1	4.1
	3	0.58	1.01	0.06	-0.80	0.82	-0.7	4.0
PurpleAir PA-II	1	0.95	1.68	0.03	-3.06	0.51	5.0	7.0
	2	0.95	1.63	0.03	-2.84	0.49	4.7	6.7
	3	0.95	1.58	0.03	-2.08	0.48	4.8	6.7
SainSmart Pure Morning P3	1	0.76	1.52	0.05	-2.34	0.69	3.5	5.3
	2	0.77	1.61	0.05	-2.19	0.70	4.6	5.9
	3	0.74	1.31	0.05	0.06	0.62	3.5	5.0
Shinyei PM Evaluation Kit	1	0.75	1.18	0.04	-1.48	0.59	0.9	4.5
	2	0.73	1.13	0.04	-1.07	0.60	0.7	4.5
	3	0.75	1.03	0.03	-1.29	0.52	-0.9	4.2
TSI AirAssure	1	0.73	1.10	0.04	1.61	0.60	2.9	5.1
	2	0.74	1.08	0.03	3.66	0.57	4.7	6.0
	3	0.72	1.01	0.03	3.81	0.56	4.0	5.6
Uhoo	1	0.00	0.09	0.11	31.11	2.03	15.4	17.7
	2	-	-	-	-	-	-	-
	3	0.00	0.02	0.08	19.74	1.51	2.9	10.1
IQAir AirVisual Pro	1	0.69	1.15	0.04	-2.38	0.73	0.2	4.4
	2	0.69	1.16	0.04	-2.42	0.73	0.3	4.4
	3	0.72	1.31	0.04	-1.97	0.77	3.4	5.3

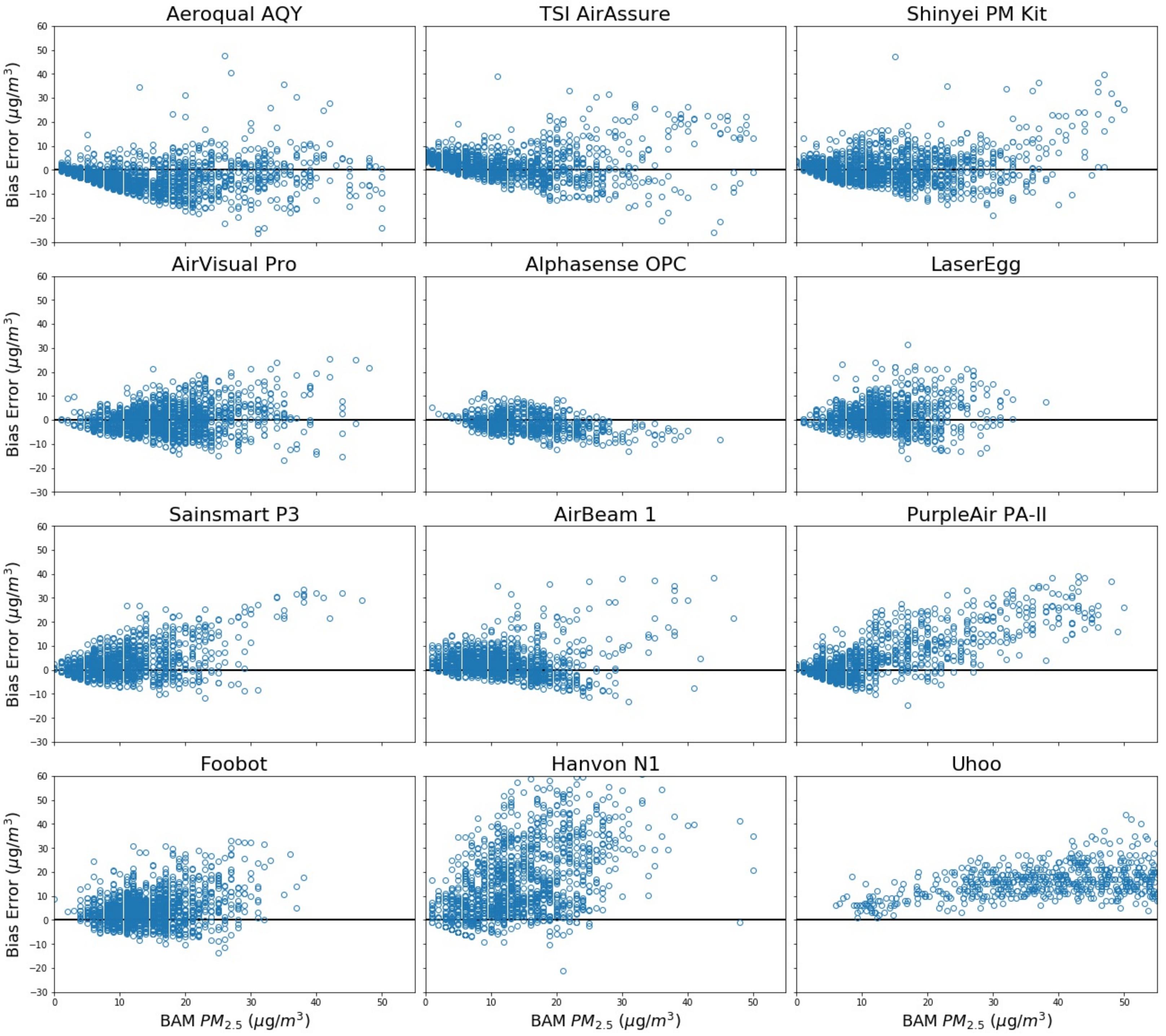
RH AND BIAS ERROR

- BAM is equipped with heater
- Sensors measure at ambient
- Some sensors correct for RH bias
- Typically, see increasing positive bias error as RH increases



PM CONCENTRATION AND BIAS ERROR

- SYSTEMATIC VS RANDOM ERROR



Thank you - Questions?

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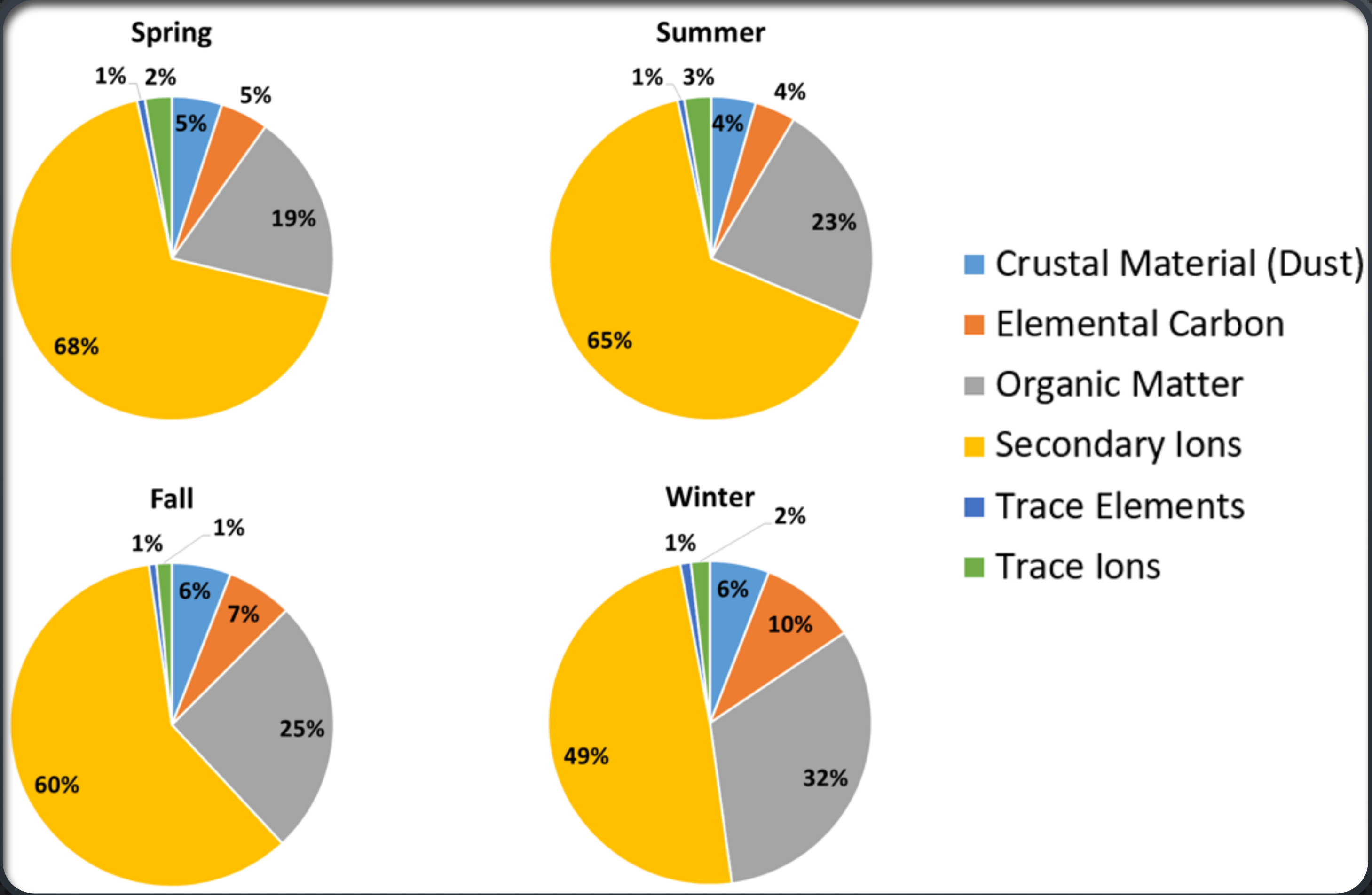
DATA RECOVERY

Sensor		Temp (°C)	RH (%)	BAM $PM_{2.5}$ ($\mu g/m^3$)		Data Recovery (%)		
Manufacturer & Model	Evaluation Dates	Mean ± SD	Mean ± SD	Mean ± SD	Max	BAM	Sensor*	Analysis (N) **
Aeroqual AQY	12/22/17 - 03/27/18	14.9 ± 5.6	48.2 ± 27.1	13.8 ± 14.4	133	88	99	84 (1917)
Airboxlab Foobot	07/14/16 - 09/15/16	25.2 ± 5.7	53.1 ± 21.6	14.4 ± 6.4	38	96	95	86 (1295)
Alphasense OPC-N2	07/10/15 - 08/10/15	24.7 ± 4.9	58.8 ± 19.5	15.6 ± 6.6	45	99	99	98 (732)
HabitatMap Air Beam 1	03/17/17 - 05/12/17	18.1 ± 5.3	53.5 ± 23.2	11.1 ± 6.6	47	98	99	98 (1317)
Hanvon N1	05/20/16 - 07/27/16	23.5 ± 6.7	54.1 ± 22.0	15.2 ± 10.3	131	98	88	77 (1264)
Kaiterra LaserEgg	08/01/16 - 09/26/16	24.2 ± 5.8	54.6 ± 21.6	14.0 ± 6.1	38	96	92	71 (951)
PurpleAir PA-II	12/08/16 - 01/26/17	12.3 ± 4.0	67.9 ± 25.3	12.1 ± 11.3	73	97	99	96 (1124)
SainSmart Pure Morning P3	03/17/17 - 05/12/17	18.1 ± 5.3	53.5 ± 23.2	11.1 ± 6.6	47	99	93	78 (1047)
Shinyei PM Evaluation Kit	02/05/15 - 04/08/15	18.0 ± 6.1	48.1 ± 26.3	15.2 ± 12.3	79	99	99	97 (1435)
TSI AirAssure	12/18/15 - 02/15/16	13.5 ± 5.7	47.6 ± 27.3	13.2 ± 11.3	69	96	93	91 (1299)
Uhoo	08/07/17 - 10/06/17	24.2 ± 6.3	55.7 ± 21.5	17.1 ± 7.3	51	99	79***	92 (1333)
IQAir Air Visual Pro	08/02/17 - 10/05/17	24.5 ± 6.2	55.9 ± 21.0	17.2 ± 7.3	51	99	99	98 (1535)
Mean of Means ± SD		20.1 ± 4.6	54.3 ± 5.3	14.2 ± 2.0				

SUMMARY STATISTICS AND INTRA-MODEL VARIABILITY FOR SENSOR TRIPLICATES

	Sensor Mean ± SD (μg/m^3)			Mean of Means
Sensor	1	2	3	Mean ± SD (μg/m^3)
Aeroqual AQY	9.8 ± 11.5	9.7 ± 11.7	9.3 ± 10.8	9.6 ± 0.24
Airboxlab Foobot	19.7 ± 10.3	17.3 ± 8.6	24.0 ± 10.3	20.3 ± 2.75
Alphasense OPC-N2	14.3 ± 6.2	10.1 ± 6.1	11.4 ± 7.0	11.9 ± 1.74
HabitatMap Air Beam 1	14.1 ± 9.3	17.0 ± 12.8	18.0 ± 14.5	16.4 ± 1.64
Hanvon N1	32.0 ± 21.7	30.5 ± 19.7	27.6 ± 17.3	30.0 ± 1.80
Kaiterra LaserEgg	15.6 ± 9.2	13.5 ± 8.2	12.9 ± 8.0	14.0 ± 1.16
PurpleAir PA-II	16.9 ± 19.1	16.5 ± 18.6	16.7 ± 18.0	16.3 ± 0.13
SainSmart Pure Morning P3	14.6 ± 12.2	15.7 ± 12.8	14.7 ± 10.6	15.0 ± 0.51
Shinyei PM Evaluation Kit	14.8 ± 13.1	14.6 ± 12.7	13.0 ± 11.5	14.1 ± 0.80
TSI AirAssure	15.6 ± 13.4	17.4 ± 13.0	16.7 ± 12.4	16.6 ± 0.75
Uhoo	32.6 ± 14.9	-	20.1 ± 11.0	26.3 ± 6.23
IQAir Air Visual Pro	17.5 ± 10.2	17.6 ± 10.2	20.7 ± 11.4	18.6 ± 1.51

RUBIDOUX SEASONAL CHEMICAL COMPOSITION OF $PM_{2.5}$



Seasonal average chemical composition of PM2.5 between 2002 and 2013 at Rubidoux monitoring station. Data adapted from Hasheminassab et al. (2014).

OPC METHODOLOGY

	Detects by:	Outputs:	*Possible* issues:
Type 1: Optical Particle Counter	Sizing individual particles by how they scatter light; counts particles per size bin (e.g., 16 size channels); converts to a "mass" concentration based on assuming particles are spheres and have a certain density.	Manufacturer dependent. Possibilities include: -Count per size bin -Estimated mass for PM_1, $PM_{2.5}$, PM_{10}	• Under-counting at high concentrations • Bias due to assumptions (e.g., density) • Measurement artifacts
Type 2: "Total scattering" type sensor	Particles as a group scatter light – this is converted to an estimated concentration (e.g. mass or number of particles per unit volume)	Usually a single numeric output: voltage, calculated concentration	▪ Upper and lower detection limit issues ▪ Potential bias due to big particles (e.g., >10 um)