Observations From Laboratory and Field-Based Evaluations of Select Low-Cost Sensor Performance

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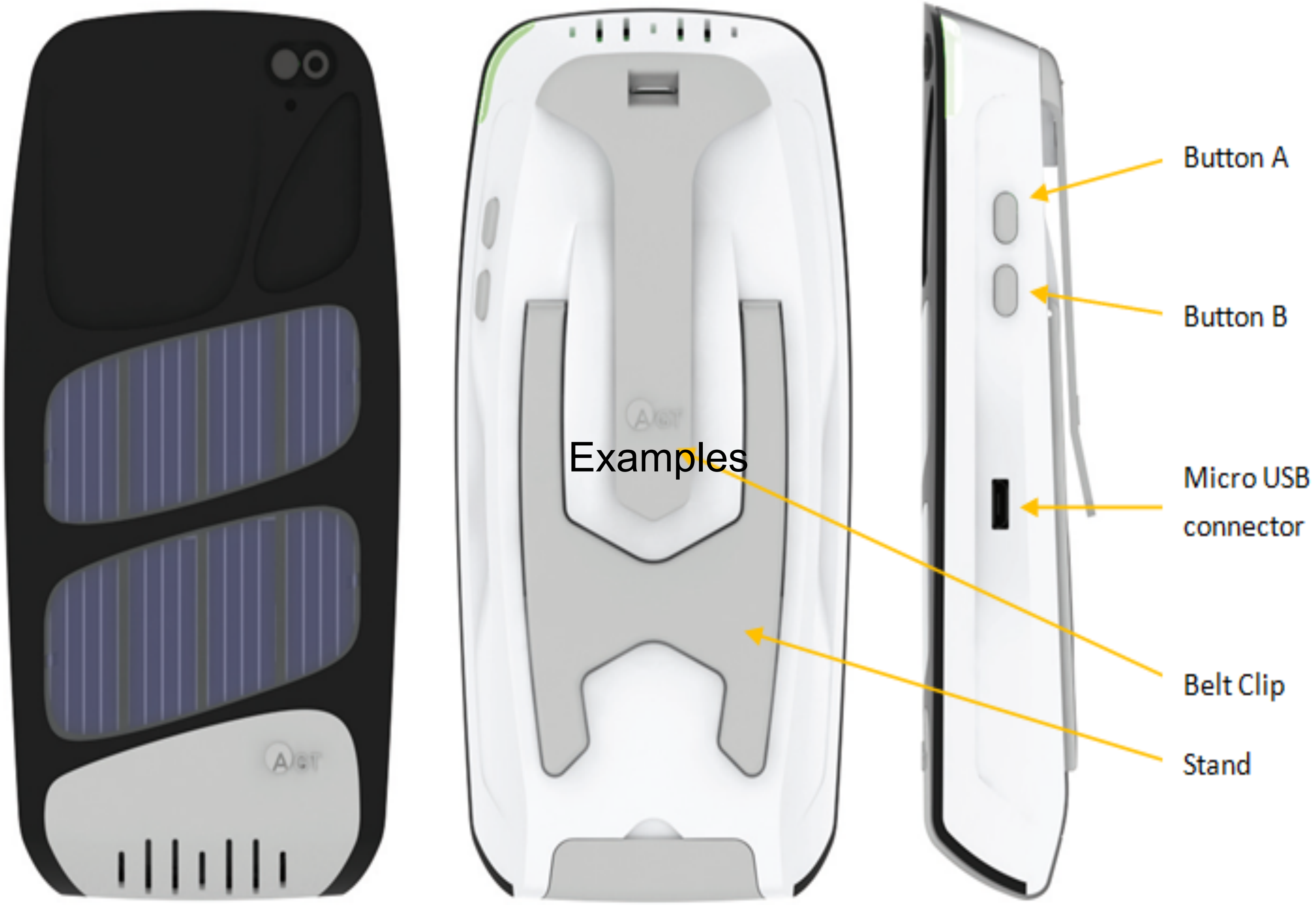
A Typical Regulatory Monitor

- Produces data of known value and highly reliable
- Stationary- cannot be easily relocated
- Instruments are often large and require a building to support their operation
- Expensive to purchase and operate (typically > $20K each)
- Requires frequent visits by highly trained staff to check on their operation
- Often operate for 10+ years before needing to be replaced

A Typical Low Cost Monitor

- Inexpensive ($100 to $5000) to purchase
- Highly portable and easy to operate (often mobile)
- Requires little or no training to start collecting data
- Inexpensive to operate (replace or recharge batteries)
- Lifetime of service not expected to exceed 1-2 years

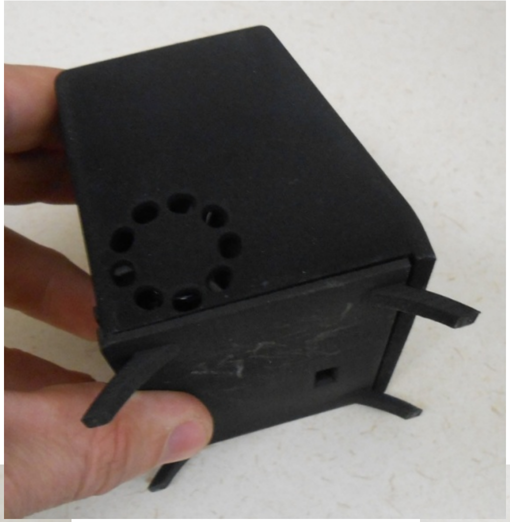
Example-AGT



Button A
Button B
Micro USB
connector
Belt Clip
Stand
Examples

Example-CanAiriT

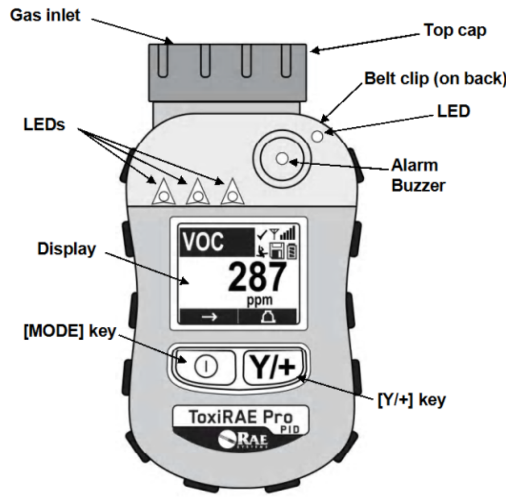
Example-Carnegie Mellon (Speck)

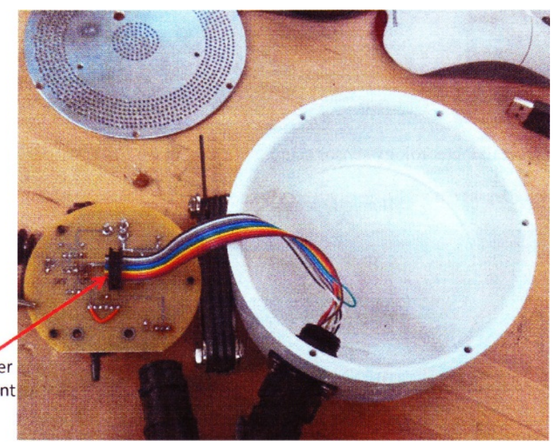


Example-Dylos

Example-Cairpol (VOC,NO_2,O_3)

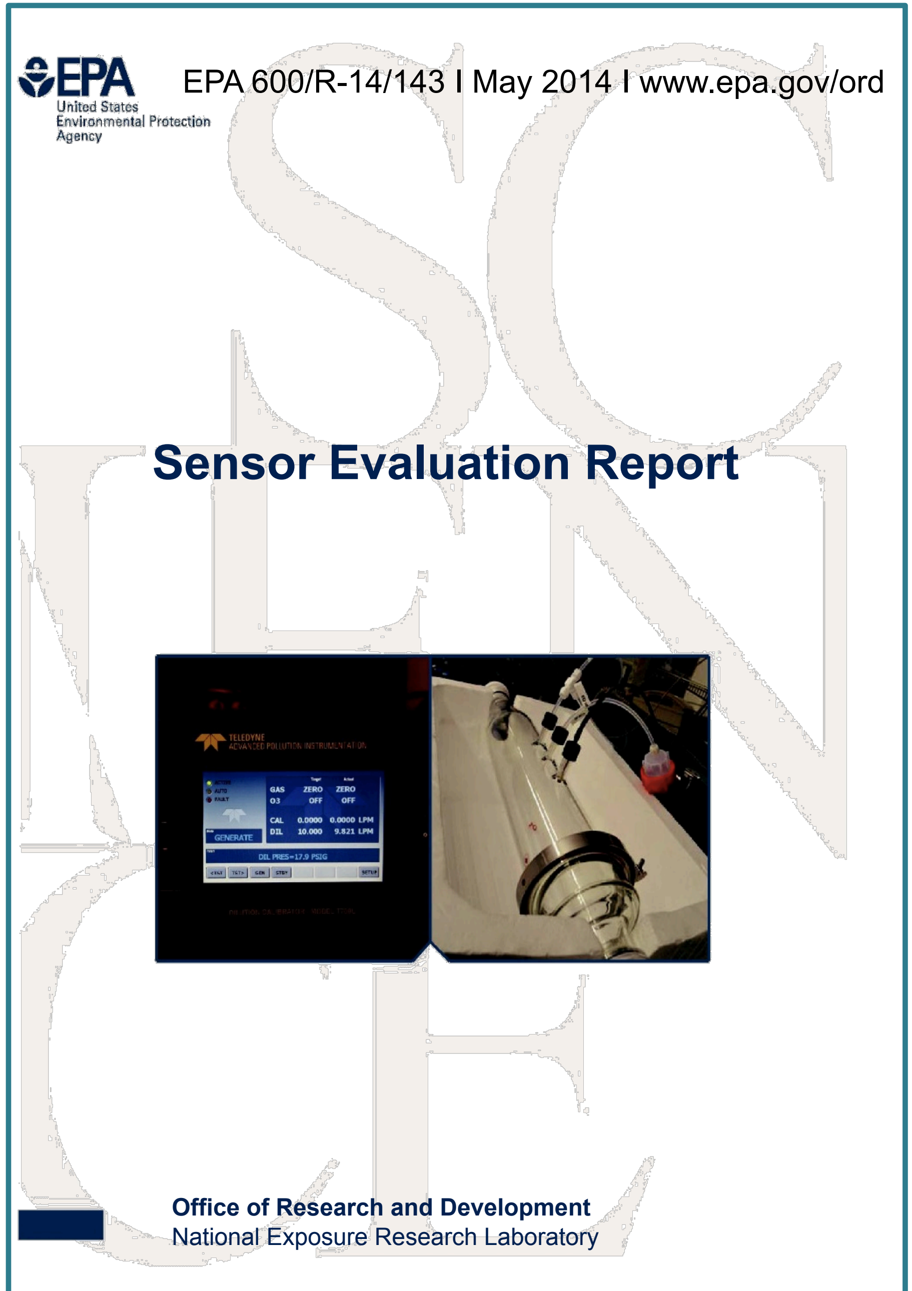
Example-UniTec, ToxRae, EPA VOC sensors





Data logger attachment

MCRADA Evaluation of NO_2 and O_3 Sensor


EPA United States Environmental Protection Agency

EPA 600/R-14/143 I May 2014 I www.epa.gov/ord

Sensor Evaluation Report

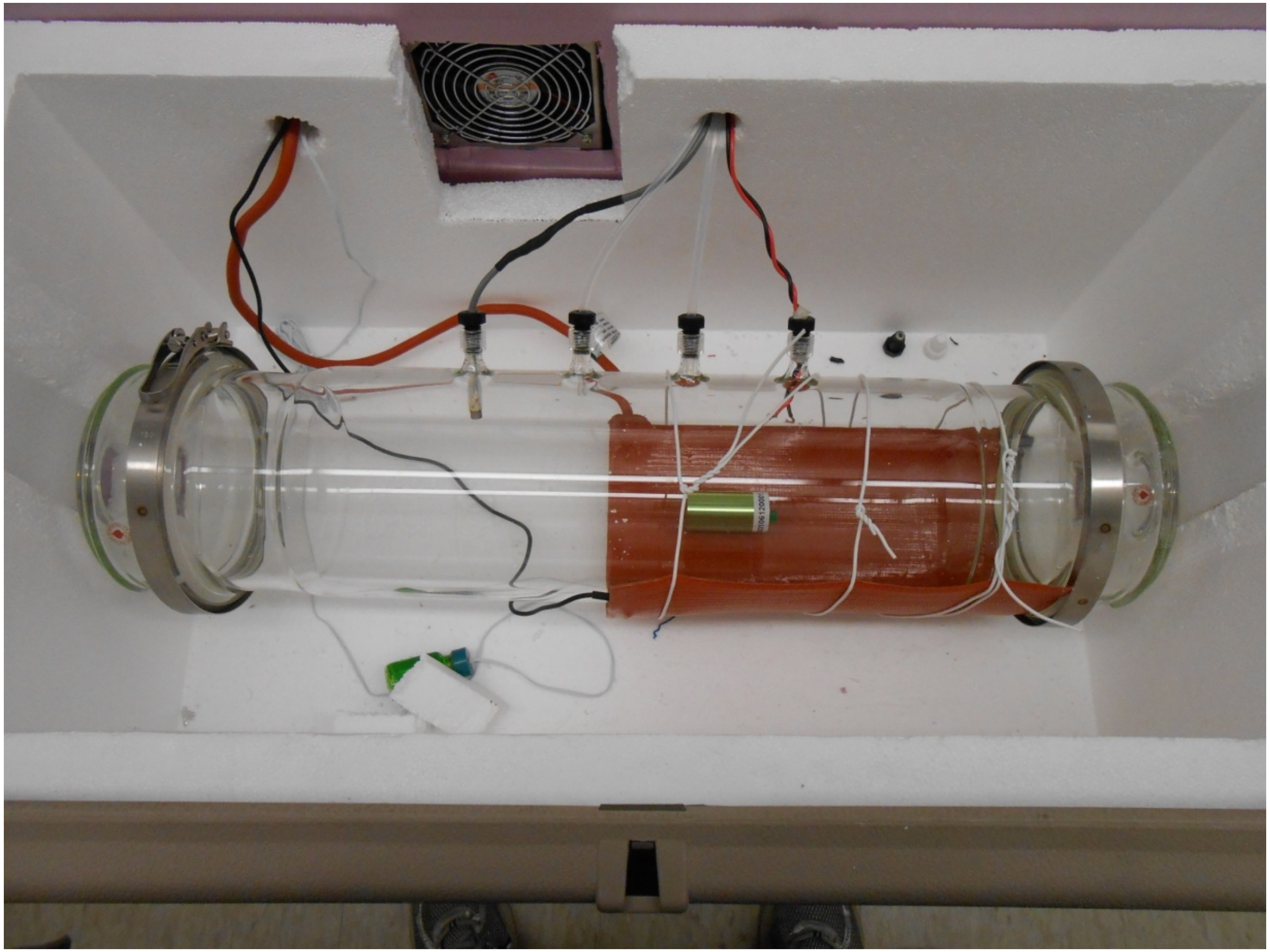
Office of Research and Development
National Exposure Research Laboratory

Technical Aspects – FRM/FEM Performance Parameters

40 CFR Part 53 Table B-1: Performance Limit Specifications for Automated Methods

Performance parameter	Units[1]	SO_2 Std. range[3]	SO_2 Lower range[2,3]	O_3 (Std. range)	NO_2 (Std. range)
1. Range	ppm	0-0.5	<0.5	0-0.5	0-0.5
2. Noise	ppm	0.001	0.0005	0.005	0.005
3. Lower detectable limit	ppm	0.002	0.001	0.010	0.010
4. Interference equivalent					
Each interferent	ppm	±0.005	[4]±0.005	±0.02	±0.02
Total, all interferents	ppm	---	---	0.06	0.04
5. Zero drift, 12 and 24 hour	ppm	±0.004	±0.002	±0.02	±0.02
6. Span drift, 24 hour					
20% of upper range limit	Percent	---	---	±20.0	±20.0
80% of upper range limit	Percent	±3.0	±3.0	±5.0	±5.0
7. Lag time	Minutes	2	2	20	20
8. Rise time	Minutes	2	2	15	15
9. Fall time	Minutes	2	2	15	15
10. Precision					
20 % of upper range limit	ppm	---	---	0.010	0.020
	Percent	2	2	---	---
80 % of upper range limit	ppm	---	---	0.010	0.030
	Percent	2	2	---	---

Sensor performance evaluation: O_3 and NO_2 lab investigations

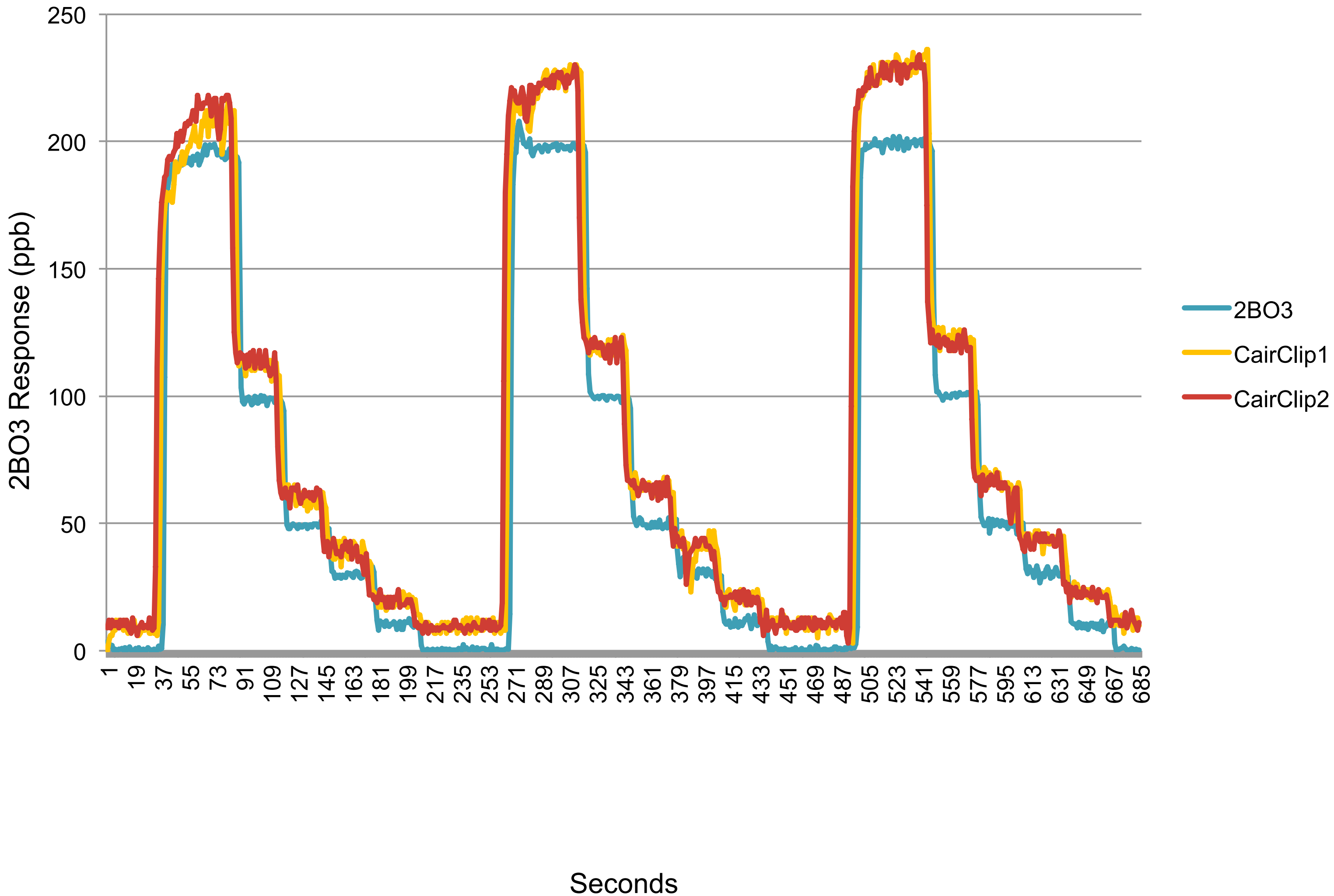


Direct sensor challenge in well defined environmental chamber with continuous FEM characterization

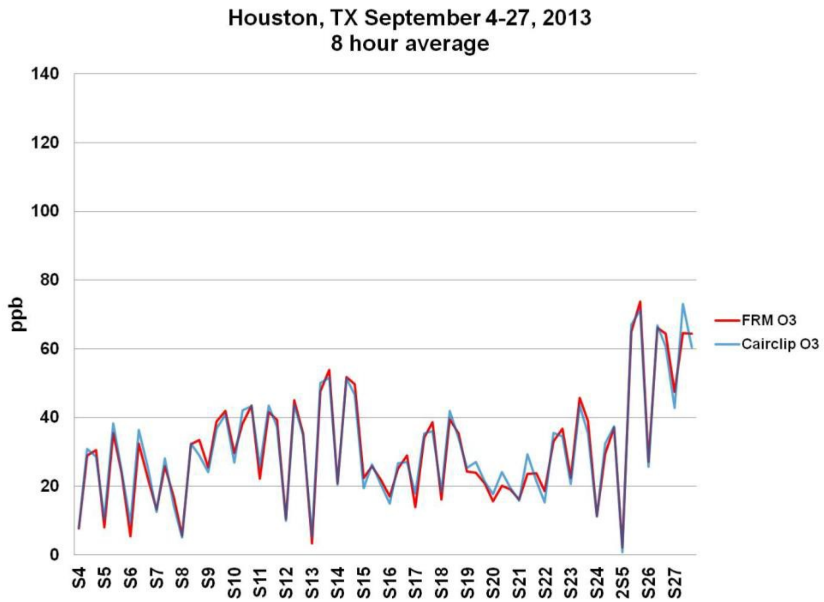
Range of challenge concentrations, temp, and RH conditions employed

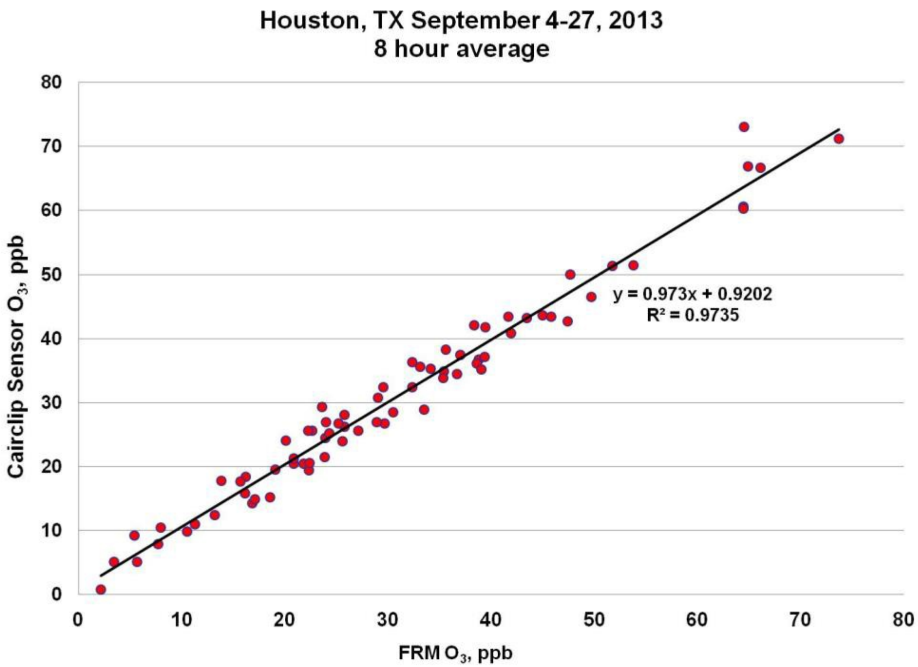
Replicate measures used to establish performance statistics

Example of Basic Performance Characteristics



DISCOVER AQ Low Cost Sensor Comparison





- Cairclip sensor data corrected by subtracting NO_2 data (as measured by NO_2 FRM) to obtain sensor O_3 results
- Sensor and FRM O_3 results averaged to 8 hours (starting at midnight) for comparison to 8 hour O_3 NAAQS
- Excellent agreement between sensor and FRM results for O_3

Typical O_3 and NO_2 Sensor Performance Characteristics

	Conditions	Response	Linearity	Precision	LDL	IDL	Res low	Res High	Lag Time	Rise Time	SO_2 int	O_3 Int	NO_2 Int
		kOhm/ppb	R^2	ppb	ppb	ppb	ppb	ppb	minutes	minutes	ppb	ppb	ppb
O3	Normal	0.4186	0.9824	10	16	12	8	14	1	5	7	NA	32
	Hot	0.2492	0.9933	14	12	18	7	38	1	6		Widely Variable	
	Humid	0.3383	0.9774	3	12	16	6	4	1	4			
	Cold	0.5484	0.9772	7	10	11	3	6	1	3			
NO2	Normal	0.6362	0.9972	1	15	10	2	2	1	5	20	off scale	NA
	Hot	0.0995	0.9919	6	14	24	6	8	1	20		Widely Variable	
	Humid	0.4526	0.9937	7	18	22	3	5	1	7			
	Cold	3.4208	0.9917	8	10	5	1	7	1	6			
CFR O3	NA	NA	NA	10	10	10	5	5	20	15	20	20	20
CFR NO2	NA	NA	NA	10	10	10	5	5	20	15	20	20	20

Direct Collocation with FEMs

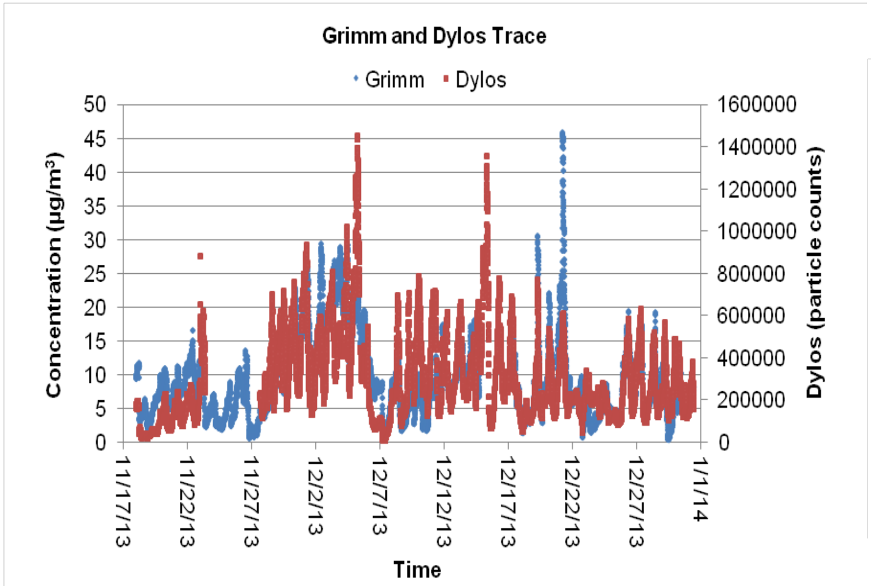
Low Cost VOC Sensor Characterization at Near Road Site

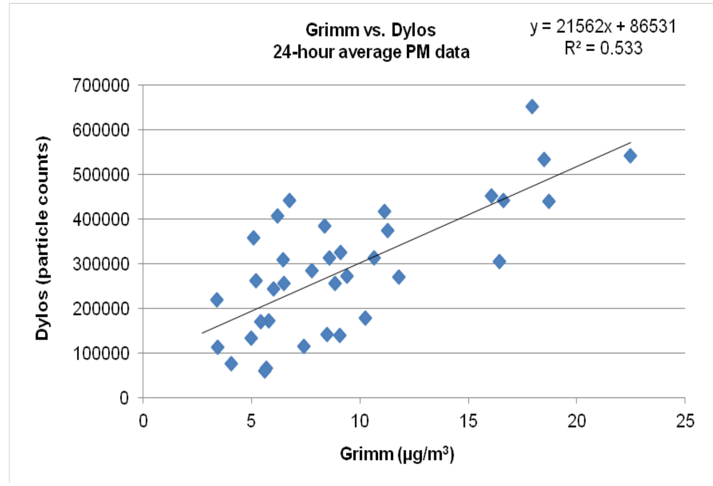
Sensor performance evaluation: lab and field

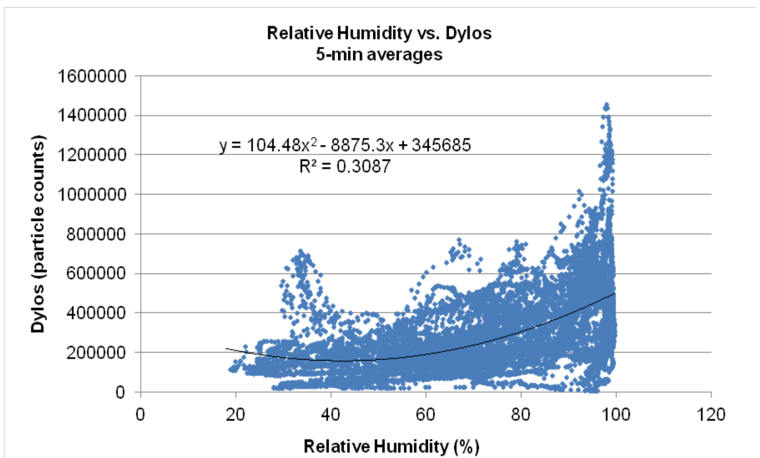
PM short-term tests – ambient, field conditions

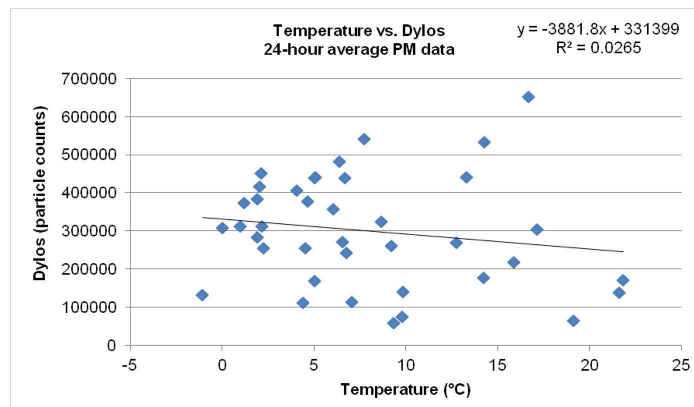
- Most low cost PM sensors provide on **modest agreement with FEM** in direct collocation challenge (CODs between 0.1 to 0.5).
- **Temperature and RH being observed as influencing factors**. Some sensors suffer from very poor sensitivity. The Dylos appears to be one of the more agreeable units even though it only provides particle counts (not mass).
- We have no information on intra/inter-variability of these sensors.

An Example of In-Depth PM Sensor Evaluation







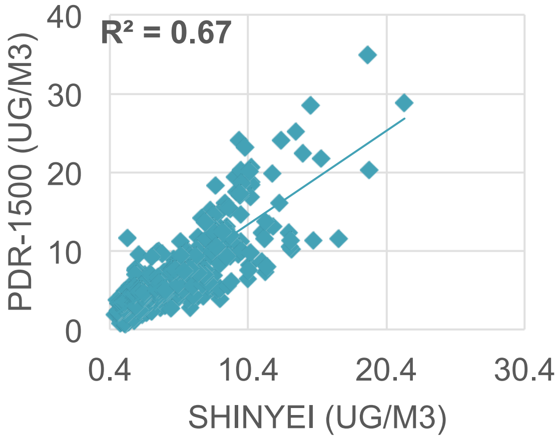


Preliminary Evaluations

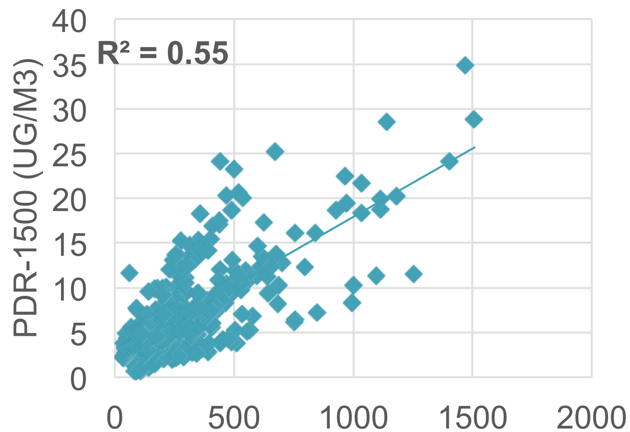
Shinyei PM sensor: light scattering-based detection principle

Week-long field test in Durham, NC determined that the Shinyei PM sensor had promising response, compared to a pDR-1500 (Thermo Scientific)

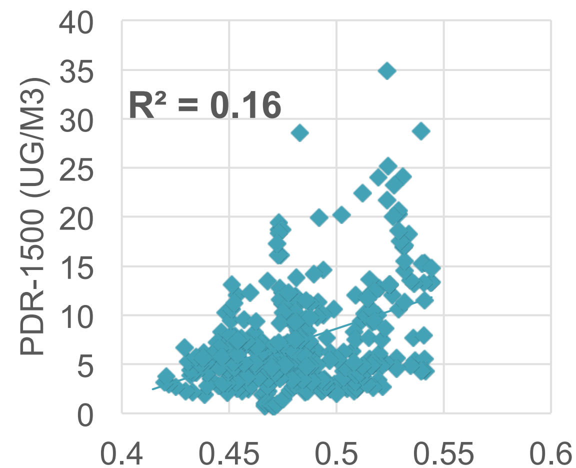
SHINYEI



DYLOS



SHARP



CAIRSENSE Project- Courtesy G. Hagler, B. Sharp, R. Williams

Low Cost PM Sensor Evaluations

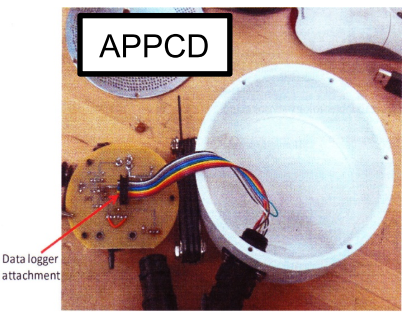
Sensor	FEM R^2 Linearity	RH Limit	Temp R^2 Linearity	Time Resolution	Uptime	Ease of Install	Ease of Use	Mobility
AirBase CanarIT (μg/m³)	0.004	100%	None	20 s	+++	++	+++	+++
CairClip PM (μg/m³)	0.064	95%	0.657	1 min	+++	++	+++	+++
Carnegie Mellon Speck (particle counts)	0.000	90%	None	1 s	+++	++	+	++
Dylos DC1100 (particle counts)	0.548	95%	None	1 min	+++	++	++	-
Met One 831 (μg/m³)	0.773	90%	None	1 min	+++	++	++	++
RTI MicroPEM (μg/m³)	--	--	>0.8*	10 s	+++	++	+	++
Sensaris Eco PM (μg/m³)	0.315	100%	0.313	Unknown	-	-	-	-

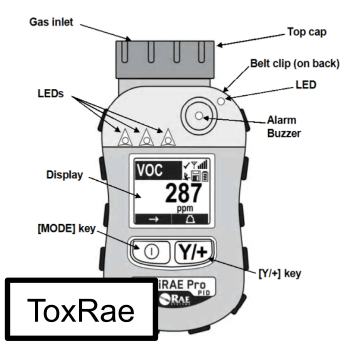
* Manufacturer has developed new programming to account for this effect

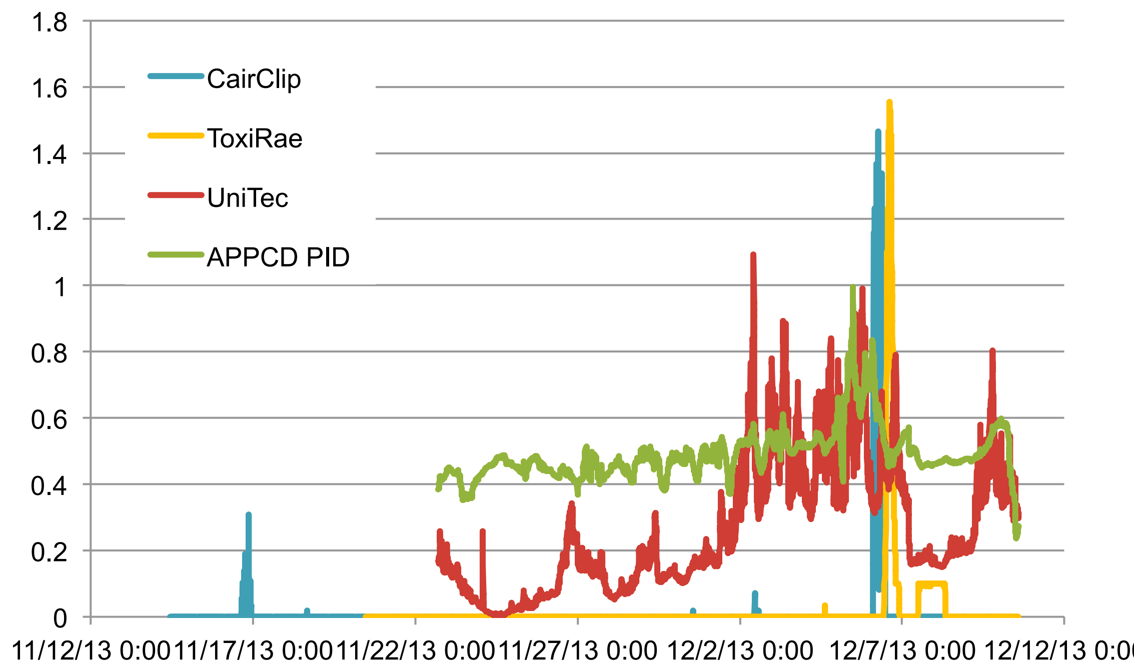
Sensor performance evaluation: lab and field

VOC sensors

- It is obvious the sensors have a wide range of sensitivities.
- Specificity is currently being determined on select models.



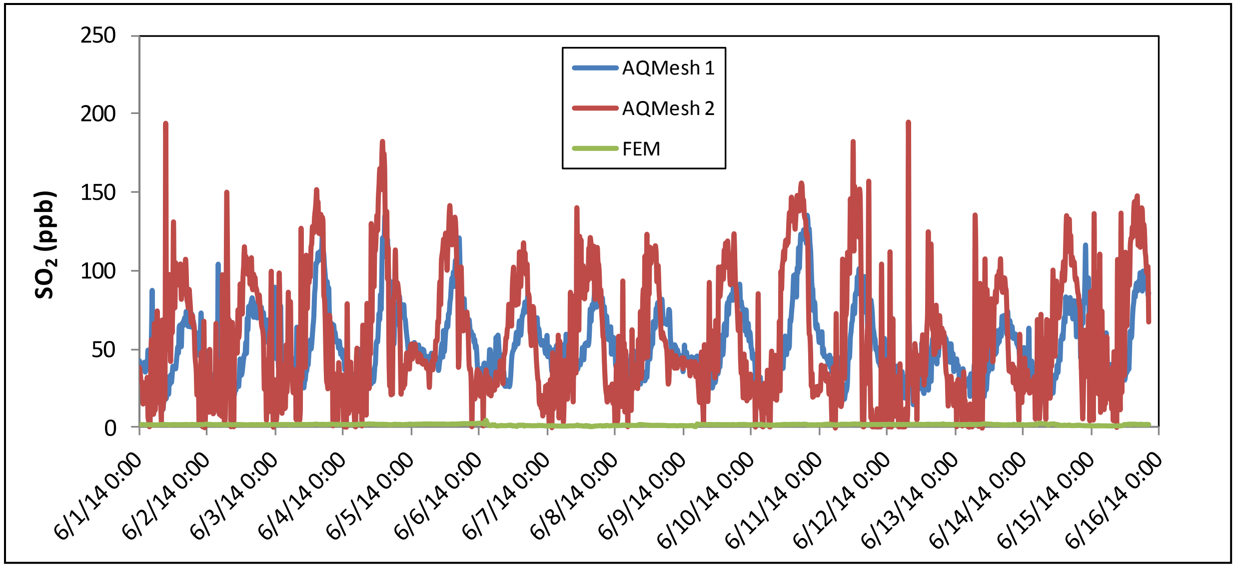


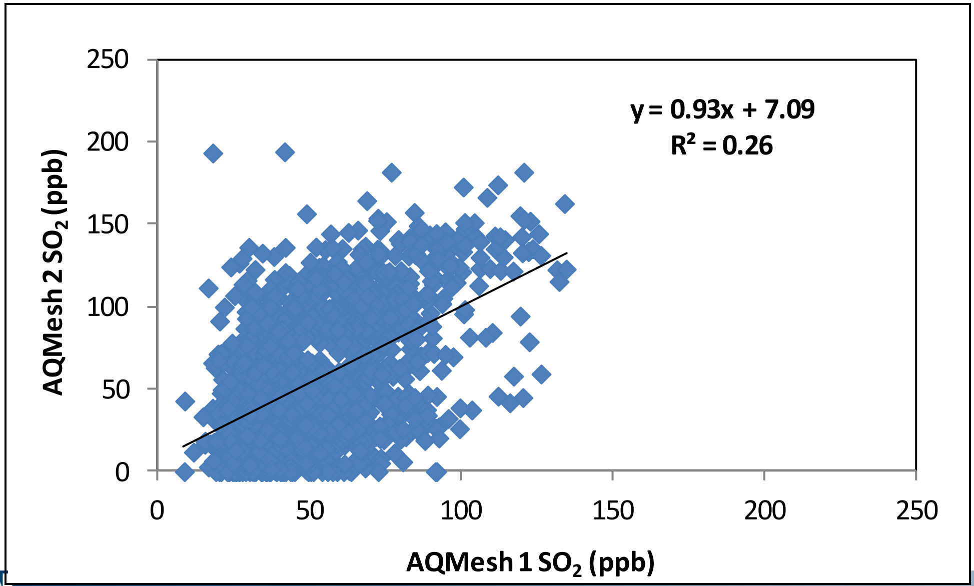


Preliminary Performance Characteristics of VOC Sensors

Sensor	R^2 Temp Linearity (°C)	R^2 RH Linearity	Time Resolution (s)	Uptime	Ease of Installation	Ease of Operation	Mobility
AirBase CanarIT (ppb)	0.4942	0.4087	20	+	++	+++	+++
APPCD PID (V)	0.0811	0.2191	1	++	-	++	++
CairClip (ppb)	0.0038	0.0307	60	+++	++	+++	+++
Sensotran Benzene (V)	NA	NA	600	unknown	-	-	-
ToxiRAE Pro PID (ppm)	0.0088	0.3597	20	++	++	+	+++
UniTec Sens-It (V)	0.0327	0.0079	60	+	-	+++	-

AQMesh
SO2 Preliminary Data





- Poor agreement between AQMesh and FEM measurements
- AQMesh readings <u>significantly</u> higher
- Poor agreement between both pods

Observed Intangible Performance Characteristics

- RH and temperature impacts may be significant for some devices
- Internal battery lifetimes range from 4 to 24 hours
- Sensor packaging can interfere with accurate measurements (reactivity)
- Wireless communication protocols are not foolproof with signal loss or difficulty being established
- Access to “raw”data may not be possible

Sensor and Data Quality-Considerations

- Weather. Many devices are temperature and relative humidity (RH) sensitive
  - Sensors often function poorly in high humidity
  - Sensors often respond differently when it is either very hot or very cold (may under or over-report true pollutant concentrations or even stop working)
  - The impact on data quality for temperature and RH effects for many low cost sensors have not been established

Unique Qualities

- <u>Battery life.</u> It is apparent that a wide range of battery options are being used. Operating periods from 3 hrs to 24 hrs have been observed
- <u>Recharge issues</u>. Very specific recharge requirements (USB to use of transformed outlet voltage) and recharge times
- <u>Orientation</u>. Some devices had to have a very specific orientation in the exposure chamber

Unique Qualities

- Sensor Interface. Some of the sensors required a discreet movement of air flow over the surface of the sensor. (Goldilocks requirement= not too much, not too little). Interface stagnation versus physical influence (cooling of sensor influences resistance and therefore output had to be considered individually for each sensor.
- Test range. There appears to be a wide range in sensor sensitivities

Communication Protocols

- WiFi, Bluetooth, hard line (direct interface with laptop, tablet or other device), flash drive download, on-screen
- Communication protocols were often less than foolproof and work around solutions had to be developed. Internal wireless security issues, cell-based signal strength and other factors had to be resolved (all were resolved)

Data Recovery/Processing

- Raw data processing (even reporting in some cases) often required interface with proprietary software data management programs. Such links prevented direct access to raw data and represented another communications linkage that had to be resolved
- Difficultly in some situations to get to raw data as the raw signal was processed via developer's software prior to being "reported" back to user

Summary

- Market surveys continue and new sensors are being integrated into field and laboratory evaluations
- Some of these devices were “prototype” and the current evaluations should not be considered definitive
- Utility of sensors to meet a specific monitoring need varies greatly. Need for careful user evaluation before use
- Lack of available information on intra and inter-variability of any given sensor
- Many low cost sensors are not designed for true ambient placement but users might be tempted to use them inappropriately for that purpose

Thank You

- If interested, you can join a monthly EPA and other interested parties webinar series on low cost sensor applications
- A great resource for you is the following website

(www.epa.gov/heasd/airsensortoolbox)