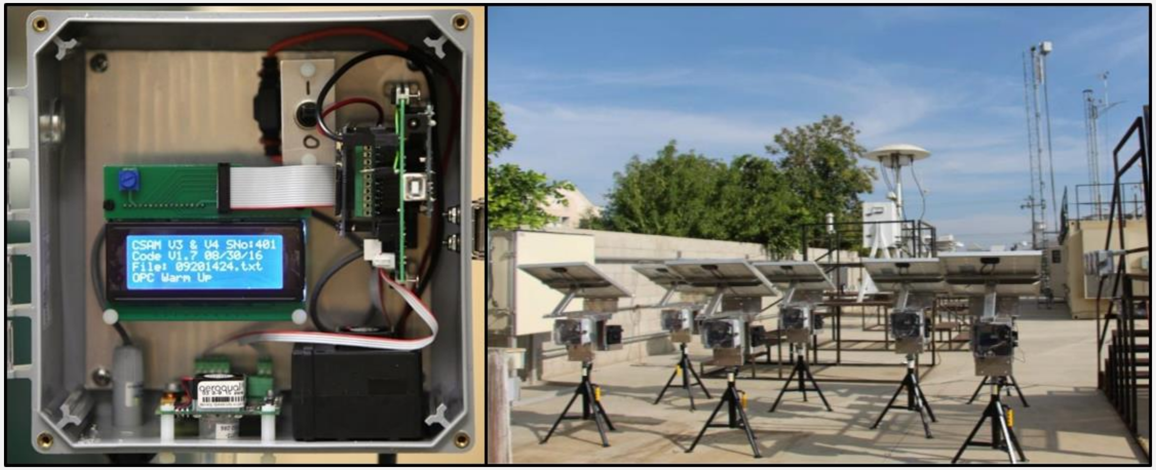
Field and Laboratory Evaluation of an Ozone Sensor



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Background and Purpose

- **Emergence of portable, low-cost air sensors has led to an increased desire to determine their value for air quality monitoring.**

- **EPA and SCAQMD have been actively involved in…**
  - **Developing and testing sensor technologies**
  - **Promoting informed sensor use, deployment, and data interpretation**

- **The performance of low-cost gas phase sensors is not well defined…**
  - **Possible co-reactivity to interfering species**
  - **Unknown environmental effects (RH, temperature)**
  - **Unknown drift, ageing and other operational factors**

Study Goals

- Develop a small, portable, low cost multi-pollutant air monitoring sensor pod
- Select and incorporate a low cost gas sensing sensor (GSS)
- Characterize performance of the sensor pod under real-world ambient air (California) and laboratory test conditions
- Evaluate sensor performance using Federal Equivalent Monitors or research grade instrumentation using a continuous monitoring approach

Study Approach

- EPA worked with South Coast Air Quality Management District's, Air Quality Sensor Performance Evaluation Center (AQ-SPEC) to deploy an EPA designed and constructed multi-pollutant sensor pod (CSAM-Citizen Science Air Monitor)
- 3 Primary Evaluation Phases of study
  - Phase 1: RTP Field Test
    - CSAM ozone sensors operated under laboratory and then ambient conditions for operational shake down
  - Phase 2: Field Performance Evaluation
    - CSAMs collocated with regulatory monitors under ambient conditions
  - Phase 3: Laboratory Performance Evaluation
    - CSAMs challenged with different pollutant concentrations and temperature and RH conditions

Citizen Science Air Monitor (CSAM)
Version 4

CSAM

Ozone Sensor

CSAM Full Assembly

Sensor/Manufacturer	**Parameter Measured**	**Approximate total cost (USD)**
OPC-N2 (AlphaSense)	$PM_{1.0}$, $PM_{2.5}$, PM_{10}	$500
SM-50 (Aeroqual)	**Ozone (Gas Sensing Sensor)**	**$500**
Adafruit AM 2315	Relative Humidity	$200
Adafruit AM 1289	Temperature	$200
Grape Solar 1289	Solar Panel	$500
Arduino Mega with Adafruit SD	Microprocessor	$400

CSAM Laboratory Design Requirements

- Robust design with EPA-designed circuit boards
- Low cost components of previous EPA use/selection
- Micro-processor controlled for ease of use
- Weather proof (wind/rain)
- Low wattage (energy use)

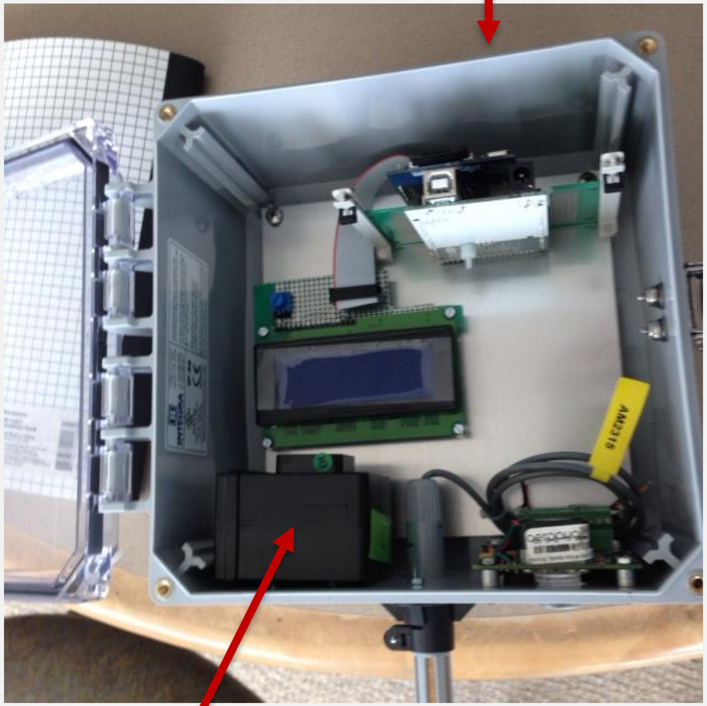
Lessons learned:

- SM-50 yielded nearly 1:1 response under lab test conditions with direct challenge to multipoint ozone test gas

- OPC-N2 PM sensor impacted ozone sensor performance

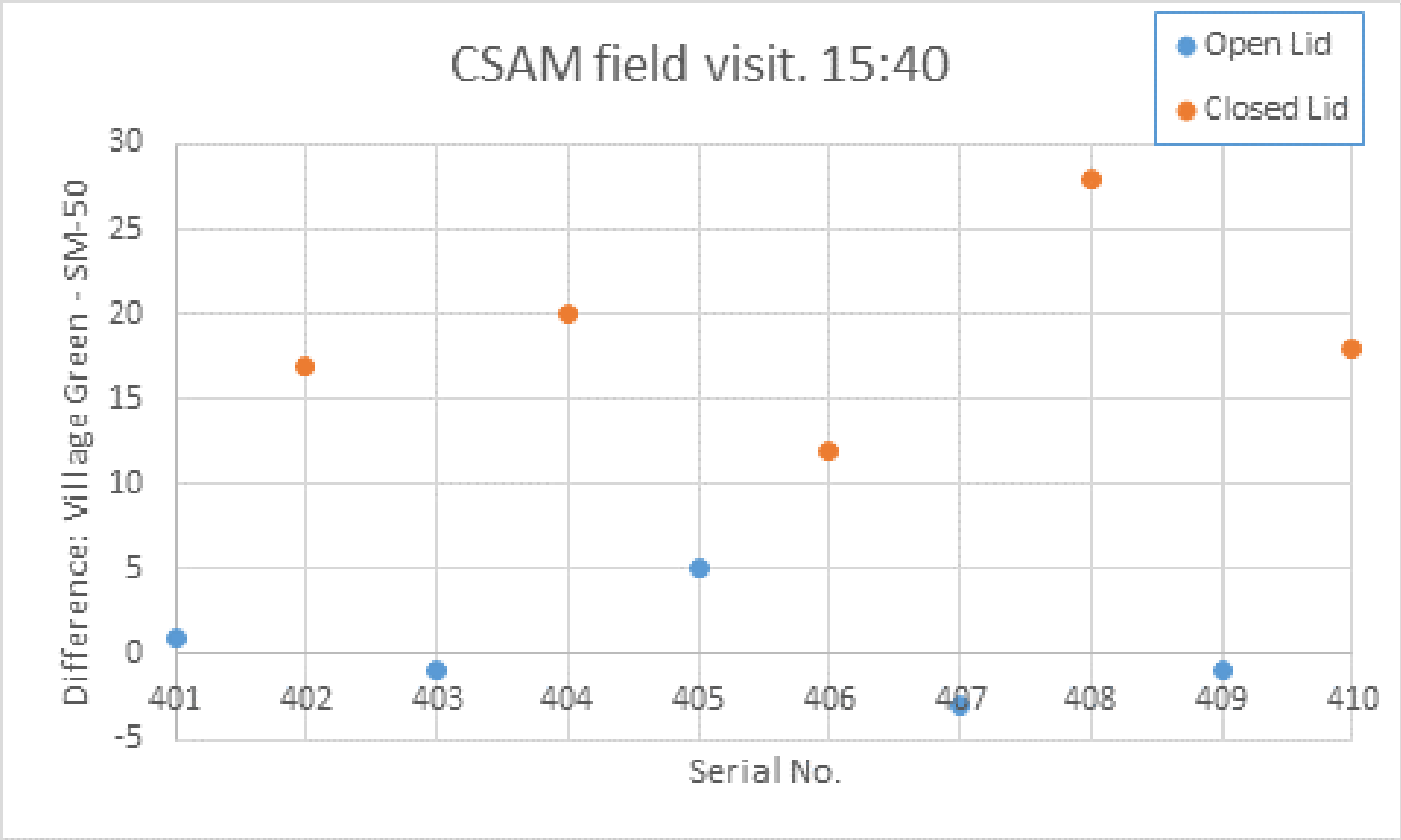
- Influence established during shake down tests

NEMA box



OPC-N2 PM sensor

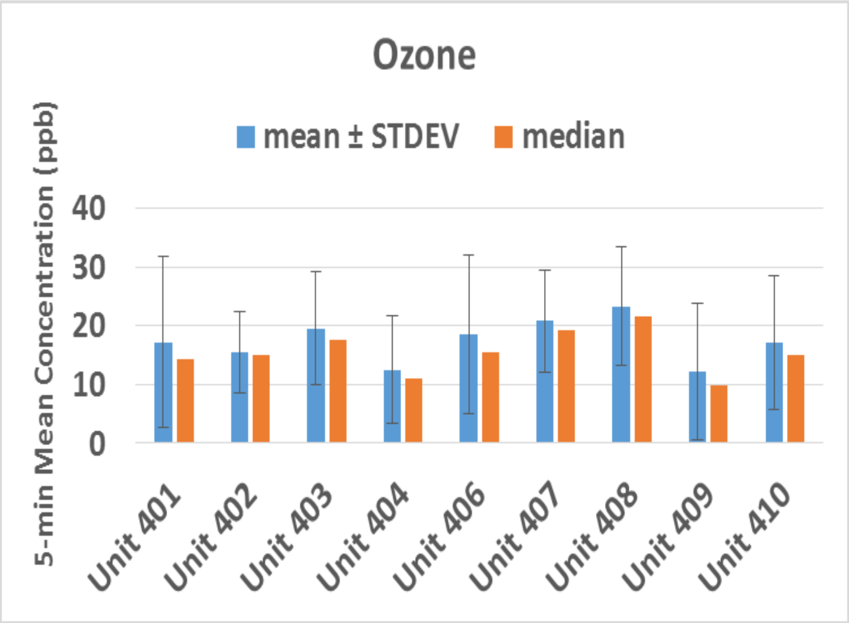
Phase 1: RTP Field Test Results

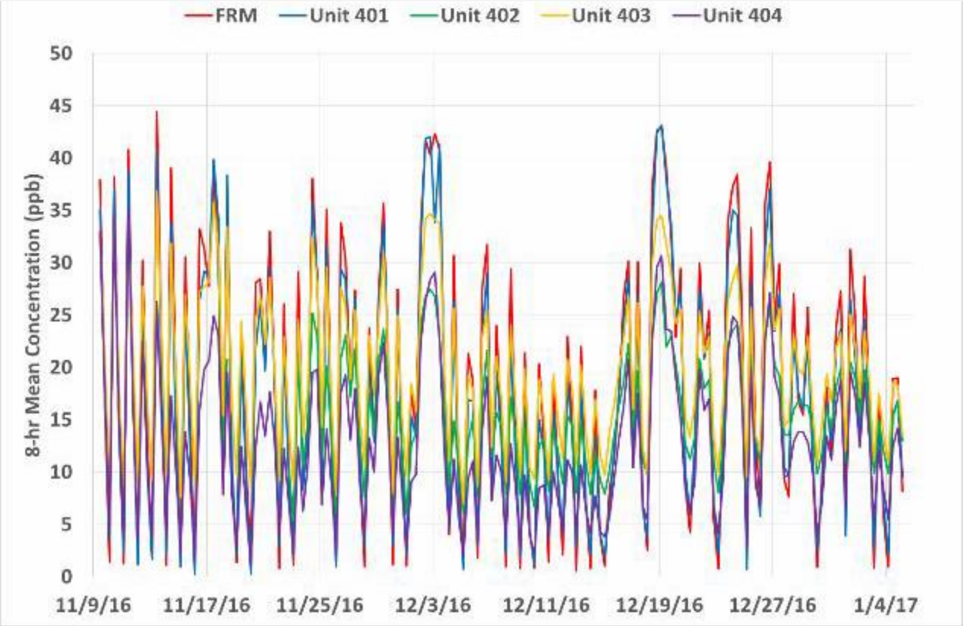


Tests indicated closed NEMA box with OPC-N2 operational (positive pressure) conditions resulted in significantly reduced SM-50 response (difference of SM-50 response and local Village Green FEM ozone sensor (2B Tech) reading. Louvered vent holes in NEMA case resolved SM-50 issue

Phase 2: AQ-SPEC Field Collocation Evaluation at Riverside-Rubidoux AMS

Results





High frequency measures (5 minute) revealed good CSAM precision between individual pods and general agreement (R^2 = 0.86-0.98) with collocated FEM)

EPA United States Environmental Protection Agency

AQ-SPEC Air Quality Sensor Performance Evaluation Center

Results

Phase 2: AQ-SPEC Field Collocation Evaluation

Ozone (5-minute Comparisons)

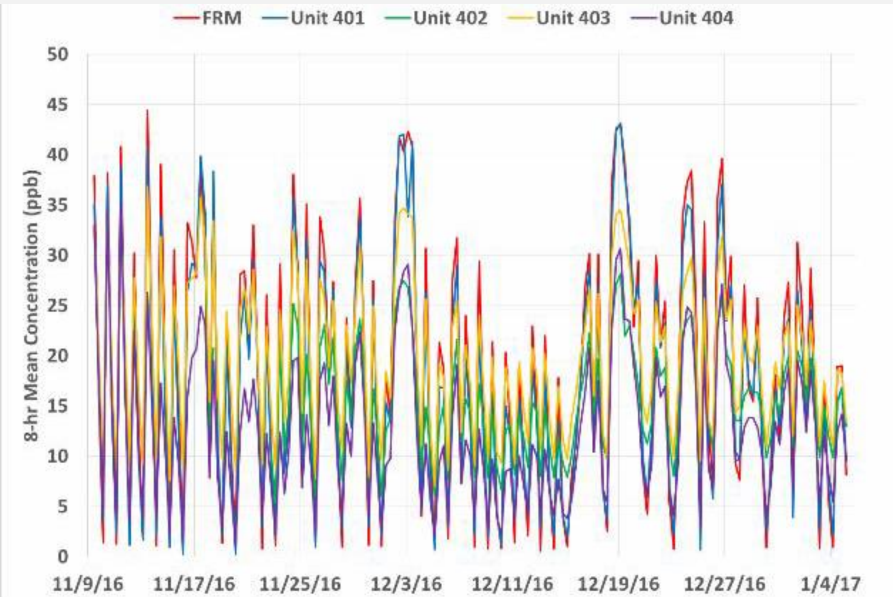
Univariate Statistics (ppb)	FEM	Unit 401	Unit 402	Unit 403	Unit 404	Unit 406	Unit 407	Unit 408	Unit 409	Unit 410
mean	18.9	17.3	15.5	19.6	12.5	18.6	20.8	23.3	12.3	17.2
median	16.9	14.3	14.9	17.6	10.9	15.4	19.2	21.6	9.9	14.9
SD	15.9	14.6	6.9	9.6	9.2	13.5	8.7	10.1	11.6	11.3
Count (#)	15319	16304	12733	16307	16304	16305	16304	16303	16304	16304
Recovery (%)	93.3	99.3	77.5	99.3	99.3	99.3	99.3	99.3	99.3	99.3

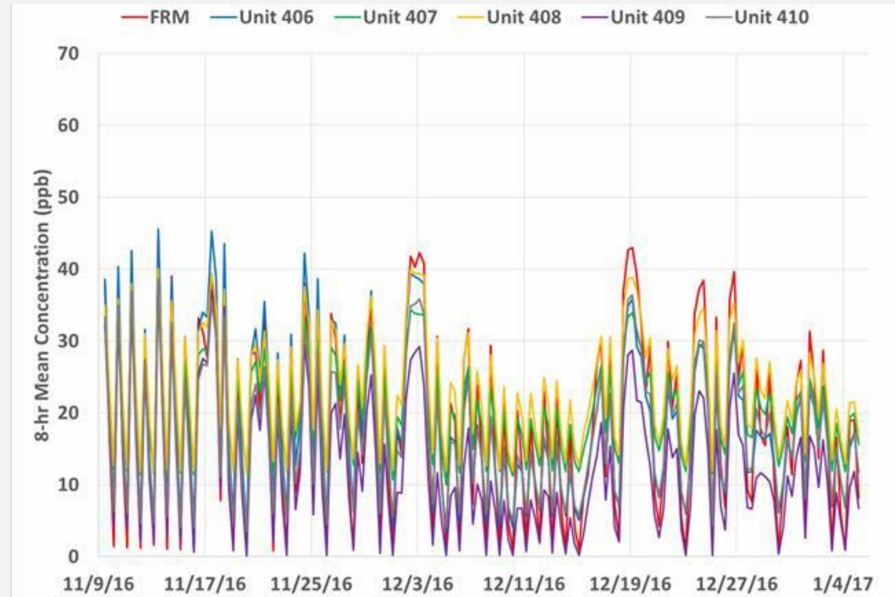
5 minute average	#401	#402	#403	#404	#406	#407	#408	#409	#410
Slope	1.0621	2.0249	1.594	1.5779	1.0978	1.7731	1.5367	1.2618	1.3563
Intercept	0.0844	-13.256	-12.845	-1.3013	-1.9282	-18.511	-17.457	3.0019	-4.8449
R^2	0.9524	0.8563	0.9394	0.8367	0.877	0.9379	0.9538	0.8549	0.9339

FEM comparison versus Thermo 49i

Example Results

Ozone (8-hour Average)





- **Excellent data recovery**
- **Low inter-sensor variability**
- **Excellent correlation to FEM instrument (R^2 = 0.86-0.98)**
- **CSAMs tend to underestimate ozone**

United States Environmental Protection Agency

Results

AQ-SPEC Air Quality Sensor Performance Evaluation Center

5 min

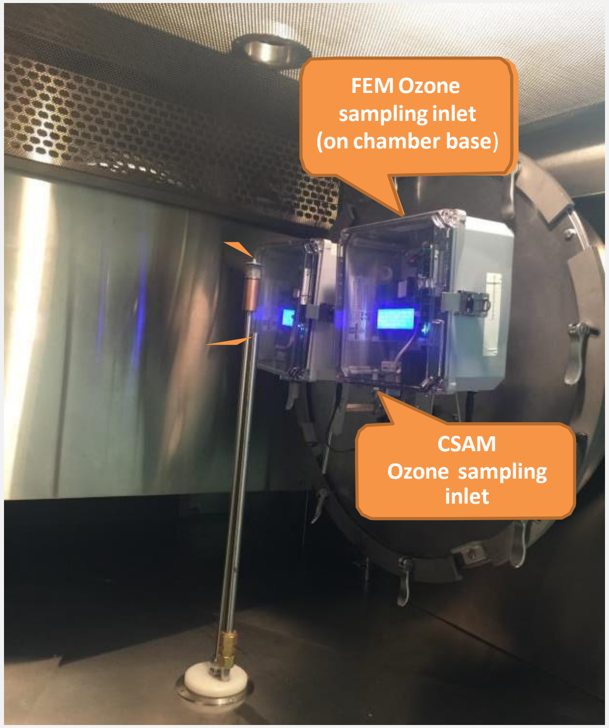
R^2	FEM	Unit 401	Unit 402	Unit 403	Unit 404	Unit 406	Unit 407	Unit 408	Unit 409	Unit 410
FEM	1									
Unit 401	0.9524	1								
Unit 402	0.8563	0.9219	1							
Unit 403	0.9394	0.9780	0.9309	1						
Unit 404	0.8367	0.9091	0.9499	0.8992	1					
Unit 406	0.8770	0.9311	0.9141	0.9468	0.8510	1				
Unit 407	0.9379	0.9796	0.9308	0.9851	0.8920	0.9698	1			
Unit 408	0.9538	0.9881	0.9109	0.9831	0.8830	0.9439	0.9881	1		
Unit 409	0.8549	0.9125	0.9575	0.9314	0.8816	0.9728	0.9520	0.9174	1	
Unit 410	0.9339	0.9860	0.9458	0.9822	0.9291	0.9552	0.9874	0.9819	0.9500	1

24 h

R^2	FEM	401	402	403	404	406	407	408	409	410
FEM	1									
Unit 401	0.9733	1								
Unit 402	0.8260	0.8501	1							
Unit 403	0.9554	0.9783	0.8859	1						
Unit 404	0.8544	0.8862	0.9388	0.8745	1					
Unit 406	0.8312	0.8585	0.8196	0.9024	0.7404	1				
Unit 407	0.9420	0.9620	0.8584	0.9826	0.8385	0.9500	1			
Unit 408	0.9665	0.9848	0.8338	0.9803	0.8382	0.8940	0.9812	1		
Unit 409	0.8042	0.8257	0.8948	0.8877	0.7868	0.9540	0.9206	0.8457	1	
Unit 410	0.9603	0.9847	0.8916	0.9862	0.9170	0.8996	0.9772	0.9747	0.8903	1

Study Approach
Phase 3: Laboratory Performance Evaluation

- **Two CSAM sensor pods were tested under controlled environmental conditions**
- **AQ-SPEC testing chambers**
  - **Stainless steel enclosure for testing Teflon-coated stainless steel enclosure for testing gases**
  - **Zero air generator, ozone generator,**
  - **Ozone FEM (Thermo 49i)**
  - **Automated system to test sensors under different temperatures, RH and pollutant concentrations**



AQ-SPEC Laboratory Testing Chamber

Study Approach
Phase 3: Laboratory Performance Evaluation

- **Evaluation Parameters**
  1. **Linear correlation coefficient**
  2. **Accuracy**
  3. **Precision**
  4. **Lower detection limit**
  5. **Effect of temperature and relative humidity**
  6. **Intra-model variability**
  7. **Data recovery**
  8. **Interference testing***

Temperature and RH Combinations

Condition	Temperature (°C)	Relative Humidity (%)	Environment
Baseline	20	40	Average
1	5	15	Cold, dry
2	5	65	Cold, humid
3	35	15	Hot, dry
4	35	65	Hot, humid

Pollutant Concentration Ramping

Ozone: 5 concentration steps ranging from very low (0-30 ppb) to very high (300 ppb).

** Only conducted for ozone; NO_2 interference evaluated*

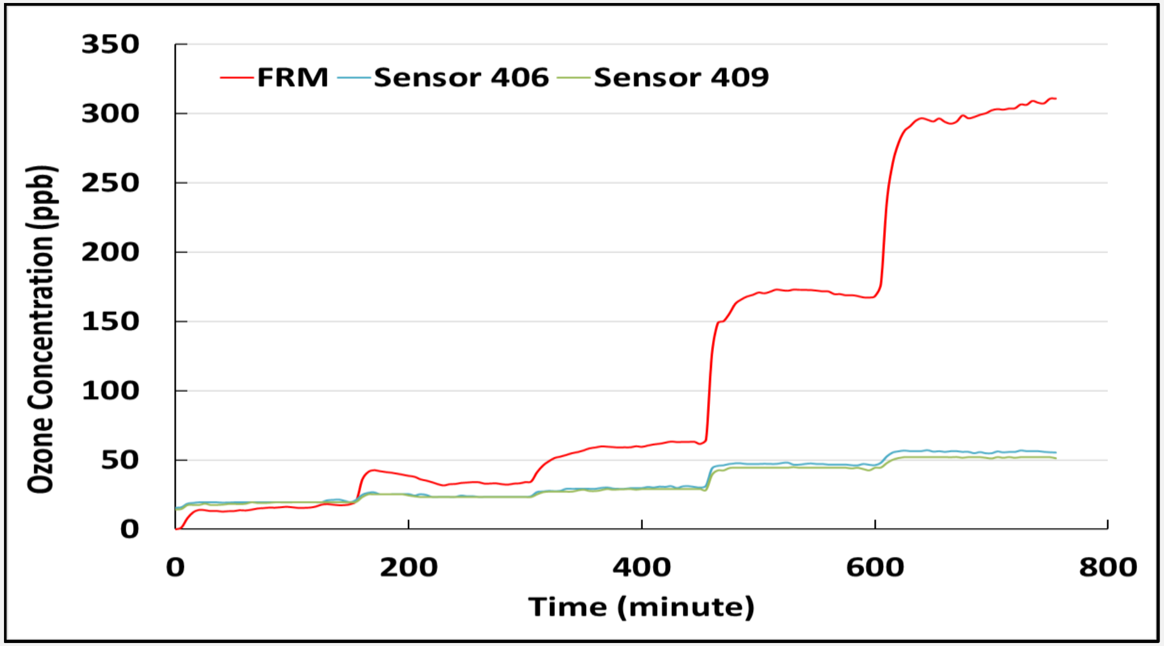
Results

Phase 3: Laboratory Performance Evaluation

Average ambient conditions (20˚ C, 40% RH)

- **CSAMs generally performed well across all parameters**

Parameter	Ozone
Linear Correlation	$R^2 > 0.95$
Accuracy	17.5 – 86.4%
Precision	> 99%
Data Recovery	~100%
Intra-model variability	$R^2 > 0.99$
Interference	None observed

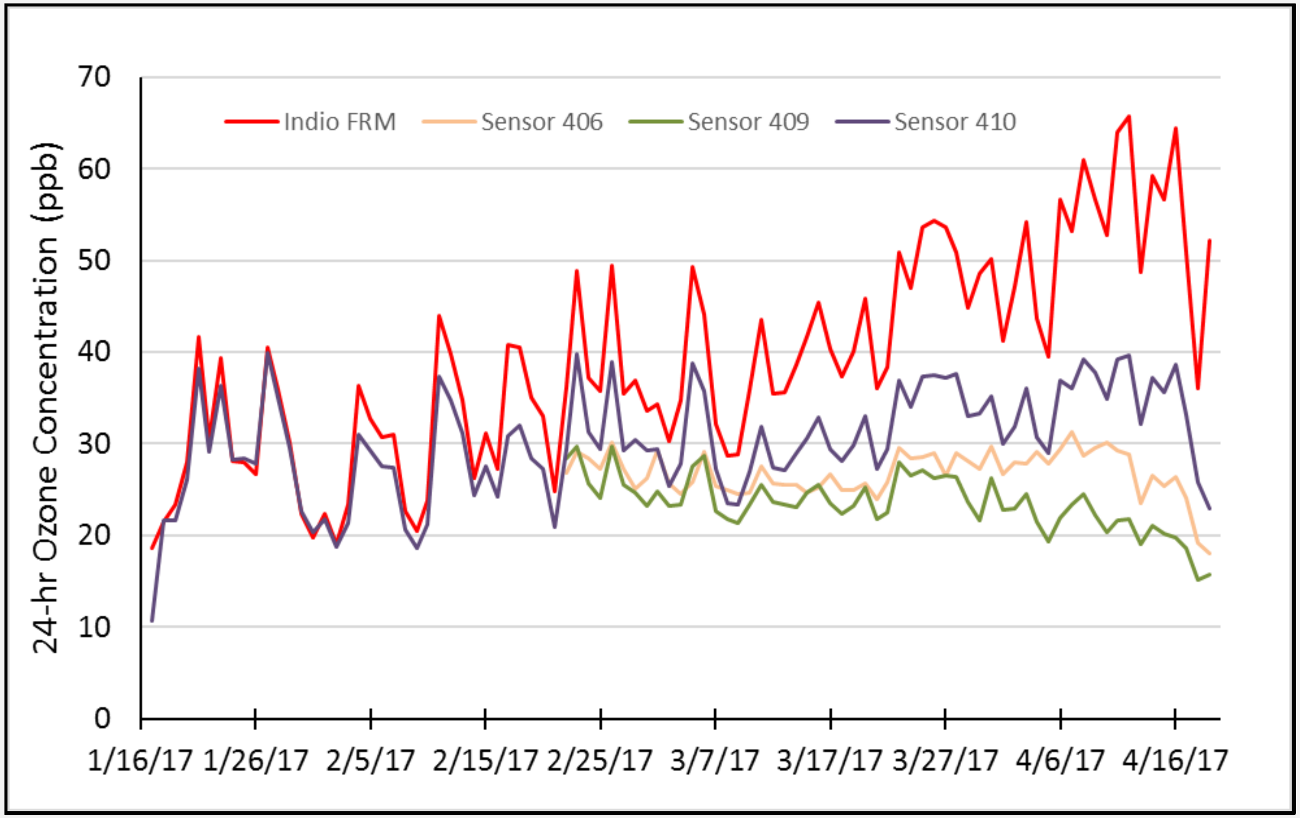


Concentration Ramping Evaluations

Results-Example of Sensor Response Change During Field Deployment

- **CSAM Ozone Data**
  - **High data recovery**
  - **Low inter-sensor variability**
  - **Correlated well with reference data**
  - **Loss of response due to decay over time (1:1 response at start of study)**

Coachella Valley 24-hr average Ozone



Summary

- CSAM pods successfully built and evaluated in the field and laboratory
- Evaluation findings:
  - Good general intra-pod precision (field and laboratory tests)
  - Excellent data recovery
  - Pressurization of SM-50 results in poor performance
  - Initial calibration (~1:1) from manufacturer confirmed in laboratory
  - Field collocation yielded good agreement with FEM
  - Extensive chamber testing yielded good linearity with FEM but variable response error over test range
  - Sensor response degradation evident during field deployment and indicative of need for repetitive sensor calibration during use

Resources and Contact Information

https://www.epa.gov/air-sensor-toolbox

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