New Paradigm for Air Pollution Monitoring

2014-2018 Progress Report

Air and Energy Research Program

Ron Williams-US EPA

April 30, 2018

Presentation Goal

The US EPA's Office of Research and Development (ORD) and its partners has been involved in emerging air quality sensor research involving a wide range of activities. Today's goal is to share with you highlights of research associated from 2014 to 2018

Disclaimer

Use of trade names or identification of commercial products does not constitute official recommendation or endorsement and are solely provided for information purposes

Emerging Technologies Staff

- Ron Williams (NERL). Sensor evaluation and development/Village Green/Citizen Science/E Enterprise and Survey and Scan.
- Vasu Kilaru (NERL). Big data considerations, data standards and infrastructure
- Sue Kimbrough (NRMRL). Village Green and KC TRAQS
- Steven Feinberg (NRMRL/ORISE). Sensor evaluation data analytics
- Teri Conner (NERL). Sensor evaluation and Village Green analytics
- Andrea Clements (NERL). Sensor Evaluation
- Stephen Reese (NERL/ORISE). Citizen Science
- Amanda Kaufman (OAQPS). Citizen Science
- Michael Breen (NERL). Time activity and APP model development
- Brian Gullett (NRMRL). Aerial sensor platforms
- Amara Holder (NRMRL). Black carbon detection and analysis
- Paul A. Solomon (NERL). Sensor development and evaluation, stationary and mobile platforms
- Surender Kaushik (NERL). Sensor development and evaluation, stationary and mobile platforms

Emerging Technologies Staff

- Rachelle Duvall (NERL/NRMRL). Village Green and citizen science
- Jesse Bash (NERL). Ground and aerial-based ammonia detection
- Jim Szykman (NERL). Ground, aerial, ship-based environmental measures
- Maribel Colon (NERL). Citizen Science
- Stacey Katz (NERL). Innovation and its Application
- Gail Robarge (NERL). Innovation and its Application
- David Holland (NERL). Data fusion
- Sheri Hunt (NCER). STAR
- Richard Callan (NCER). STAR
- Kirk Baker and Matt Landis (Wildfire Challenge)
- Gayle Hagler (NERL). RETIGO/Village Green/E Enterprise
- Extensive Regional, Program Office partnerships (R1-10); OAQPS, OECA
- Extensive External partnerships (ACLIMA, NASA, NOAA, USFS, USGS, UN)

New Technologies - Where to Start?

The Sensor Reality

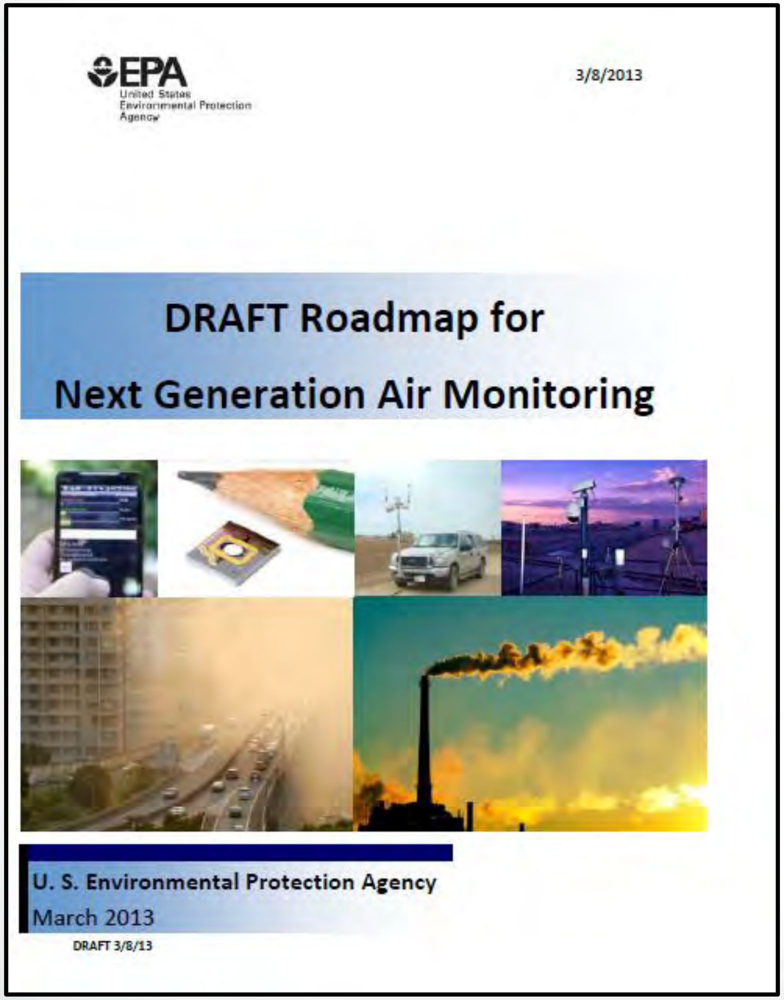
<u>Current Technology</u>

1. Expensive
2. Often snapshot
3. May require expertise to use
4. Often delays for lab analysis
5. Established QA protocols
6. Operated by gov, industry, researchers
7. Data stored and explained on gov websites

<u>New Technology</u>

1. Low cost
2. Often continuous
3. <u>Sometimes</u> easy-to-use
4. Real-time w/o lab analysis
5. QA protocol gaps
6. Collected by communities and individuals, commercial groups
7. Data crowd-sourced, shared and accessed on non-gov sites

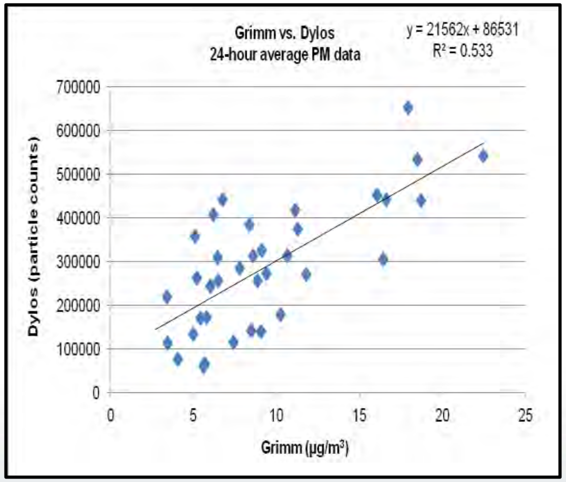
A Call for Research



- **Determine the state of the science (Discovery)**
- **Where could EPA make greatest immediate impact (Evaluation)**
- **Integrate into research portfolio (Application)**

Technology and Information Sharing

- Emerging technologies represent challenges for stakeholder use. Research focus:
  - Discovery of new technologies
  - Evaluation of sensors
  - Application of new technologies in research efforts to determine their value



Emerging Technologies Research Agenda

1) Investigate emerging technologies and potential to meet future air quality monitoring needs (ongoing)
2) Establish market surveys of commercially-available air quality sensors (ongoing)
3) Conduct extensive literature survey on the state of sensor technologies (ongoing)
4) Develop sensor user guides (accomplished)
5) Educate sensor developers and users on the state of low cost sensors (ongoing)
6) Facilitate knowledge transfer to wide range of stakeholders (ongoing)
7) Work with sensor developers to speed up development (ongoing)
8) Support ORD's Sensor Roadmap by focusing on high priority issues (ongoing)
9) Establish highly integrated research efforts across EPA (accomplished)
10) Apply knowledge gained in hands-on sensor deployment activities (ongoing)

Recent Activities-Some Examples

2012

ASAP workshop

Sensors Evaluation and Collaboration

2013

Air Sensor workshops

Short-term sensor field tests

Designing/building autonomous systems: Village Green Project

2014

Air sensors workshop

Short-term sensor field tests

2015

Citizen Science Toolbox

CSAM-Citizen Science

Designing/building autonomous systems: Village Green Project II

Long-term testing: Regional Methods Project -CAIRSENSE

Data visualization: RETIGO

Community training

- Workshops
- Performance testing
- Sensor system build
- Sensor data tools

Recent/Current Research Activities

2016	2018
States/Tribal Nations/others	Data sharing with stakeholders
Long-term testing: Regional Methods Project -CAIRSENSE	Summarize state of the science
Short-term sensor field tests	3rd Party Certification workshop
Design Citizen Science applications	Field Citizen Science applications
Designing/building autonomous systems: Village Green Project v. II	Release Village Green "Blue Prints"
Apply new technologies in complex field studies (DISCOVER AQ- KORUS)	Use of AirMapper, CSAMs, aerial platforms
Establish dialogue on data standards (E-Enterprise)	MAT and Sensor Collocation Guides

Data sharing

Performance testing

Sensor system build

Sensor data tools

Select ORD-Region Research Projects Involving Sensors (FY17-18)

Project / Year	Regional Partner(s)	Measurements	Location
CAIRSENSE (Being summarized)	Region 1,4,5,7,8	PM, ozone, nitrogen dioxide, CO – four sensor nodes	Atlanta/Denver
CSAM (Summarized)	Region 2	PM, NO_2, temperature, humidity – portable stations	Ironbound community, NJ
CitySpace (Being summarized)	*Region 4* *Region 6* *Region 7*	*PM – up to 20 stationary nodes*	*Memphis, TN*
AirMapper	*Region 5* *Region 10* *Region 7*	*PM, noise, temperature, humidity – portable units*	*Chicago, IL* *Portland, OR* *Kansas City, KS*
Puerto Rico EJ (Being summarized)	*Region 2*	*PM, VOCs, NO_2 – 10 portable units*	*Puerto Rico*
Southern California (Being summarized)	*Region 9*	*PM, ozone temperature, humidity – portable units- 10 portable units*	*200 mile swath of southern California*
AIRS platform	*OAQPS, UN*	*UN sensor pod, Aeroquals, Plan Tower, Purple Air*	*RTP FEM platform*

Select Research Projects Involving Emerging Technologies (FY17-18)

Project / Year	Partner(s)	Measurements	Location
E Enterprise	OAQPS, OECA, States	3rd Party certification considerations-Workshop preparation	RTP
Aerial Platforms	Multiple regions, DoD, USFS, USGS, Canada	PM, CO, CO2 other biomass and other combustion products	Oregon, Canada, VA, OK
Black Carbon detection	*Region 6, Region 7*	*Advanced micro Aethalometer*	*RTP, Houston, Kansas City*
Mobile platforms	*Region 9*	*CRADA with ACLIMA with support from Google*	*Denver, Bay area, LA and San Joaquin Valley*
Spatial/temporal Ammonia modeling	*NOAA, NASA, Europe*	Fine scale determination of atmospheric ammonia	Earth
Advanced measurements	*States, Regions, Korea*	*Ozone, select gases and aerosols*	*Utah, Great Lakes*

Select Research Projects Involving Emerging Technologies(FY17-18)

Project / Year	Partner(s)	Measurements	Location
WildFire Challenge	USFS	Multipollutant sensor pod	Open design/build challenge
STAR Grants-Community Monitoring	Carnegie-Mellon, KSU, MIT, RTI, SCAQMD, U of Wash	Low cost sensors	6 communities. High degree of citizen/community involvement
Survey and Scan	*OECA, States*	*Defining state of the science for a broad sweep of emerging technologies cost range*	*Nation-wide*
Village Green	*Region 1,3,5,6,7*	*Continuous air quality monitoring via the VG bench and AirNow*	*Chicago, DC, KS, OKC, Houston, Philly, Durham, Hartford*
Data modeling	*Duke*	*Village Green and other databases being used to leverage modeling research*	*Durham, DC*
3rd Party Certification	*International and National subject*	*Development of benchmarks of sensor performance-international*	*RTP, NC*

Sensor Technology-A Call to Discovery

- **World development of base technologies**
- **Wide range of "end-users"**
- **Sensor capabilities were unknown**
- **More questions than answers on the discovery, evaluation, and application of these devices**

Air Pollution Sensors

Highlights from an EPA Workshop on the Evolution and Revolution in Low-Cost Participatory Air Monitoring

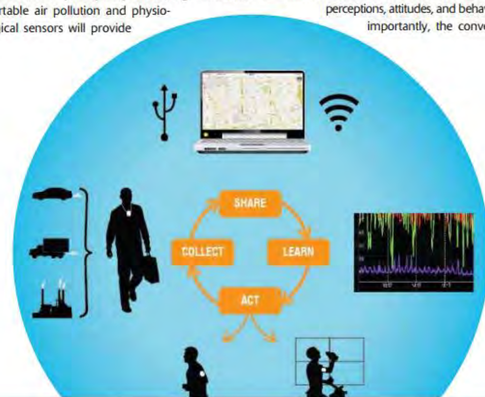
by Dena Vallano, Emily Snyder, Vasu Kilaru, Eben Thoma, Ronald Williams, Gayle Hagler, and Tim Watkins

Dena Vallano is an American Association for the Advancement of Science Fellow with the U.S. Environmental Protection Agency's (EPA) Office of Research and Development, San Francisco, CA; **Emily Snyder, Vasu Kilaru, Eben Thoma, Ronald Williams, Gayle Hagler,** and **Tim Watkins** are all with EPA's Office of Research and Development, Research Triangle Park, NC. E-mail: snyder.emily@epa.gov.

A summary overview of discussions during EPA's Apps and Sensors for Air Pollution (ASAP) Workshop, held March 2012 in Research Triangle Park, NC, where the current state of the science, data management. and community efforts involving apps and sensors were the focus. This article highlights some of the specific needs, challenges, related efforts, and potential solutions identified during the workshop talks and breakout sessions.

Air Quality Monitoring

In the near future, the status quo of air monitoring will undergo a revolution, changing from government entities and academic groups that implement short- or long-term measurements to an emerging, more democratized paradigm where citizens have the opportunity to participate in air monitoring. This is termed "participatory monitoring." Low-cost, portable air pollution and physiological sensors will provide individuals, health professionals, and public health researchers with new and unprecedented amounts of data (see Figure 1). These methods have the potential to revolutionize peoples' lives, assist in health diagnoses and treatment, and inform the research community. This new "sensor web" will customize information tailored to people's needs and actively engage them in ways that change their perceptions, attitudes, and behaviors. As importantly, the convergence of innovative sensor technologies also provides government and academic groups with the ability to supplement existing fixed monitoring station measurements with cost-effective near-source measurements.



This air monitoring revolution is possible because scientists, device manufacturers, and the open-source community continue to decrease the size and cost of environmental monitoring instrumentation. New advances in participatory measurements focus on miniaturization and real-time data output, using electrochemical, metal oxide, optical, and other principles to analyze samples; they also use onboard microelectronic devices to sense and measure pollutants such as carbon monoxide (CO) and nitrogen dioxide (NO_2).[1] These advances enable widespread applications and measurement collection outside of specially-trained scientific organizations.

Traditional regulatory-based protocols for air pollution monitors typically involve expensive—more than US$10,000—instrumentation that requires climate-controlled shelters, dedicated and costly electrical service, and siting infrastructure. In many cases, samples are collected from environmental media (e.g., air, water, soil), and require laboratory-based analyses. While advances in air monitoring currently allow online analyses that were formerly restricted to laboratory settings, these emerging instruments are limited for widespread use due to size, complexity, and cost.

The advent and proliferation of applications, or "apps," for cellular telephones have captured the imagination of technology developers and cell-phone users around the world. It is logical to couple smartphones to air pollution sensors because they already provide useful metadata like geospatial coordinates and time stamps and can provide wireless streaming of data to cloud-based resources for processing, visualization, and distribution. The following sections highlight some of the specific needs, challenges, related efforts, and potential solutions identified during EPA's ASAP workshop. Table 1 presents workshop participant highlights in technology development and community efforts in the field of sensors and apps.

Existing Sensor Technologies

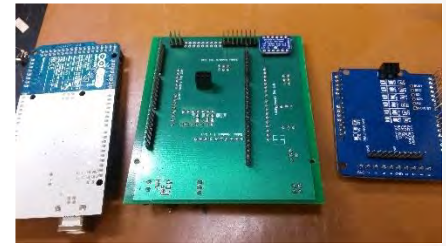
In order to take relevant measurements, it is evident that communities need information on the appropriate accuracy, precision, and range of operating conditions (e.g., concentration ranges, environmental conditions, etc.) for their devices. Thus, air quality monitoring guidelines for low-cost sensors need to address not only a number of technical specifications, but also methods on data application and interpretation.

A European Union Directive currently allows indicative measurements to supplement fixed site data, which reduces the number of required fixed monitoring sites (equivalent to U.S. ambient air monitoring stations equipped with Federal Reference or Federal Equivalent Method [FRM or FEM] monitors) and promotes alternative technologies.[2] Some participants stated that similar standards could be developed for other pollutant monitors, and an additional category could be added to

Figure 1. An example of a person fitted with a sensor (or set of sensors) that collect data related to environmental and health conditions that an individual encounters or experiences during the course of a day. These data are then transferred to a personal computer, smartphone, or web service that can simultaneously display location maps and sensor data. The user can then share this information with others (friends, family, doctors, etc.) and ultimately take appropriate actions based on this information, such as reducing exposure to high-pollution areas.

General Research Discovery Findings

Microprocessor Selection



- Wide variety of capable low cost components ($100-$300)
- Code development will be required
- It is not as easy as it sounds to integrate compounds in a stable processing environment
- Dry run of completely assembled unit a "must do" to ensure reliability

Power Selection

- 50W solar cells ~ $90 and provide direct or back-up energy supply. Need 10-12 hrs of daylight for small sensor pods
- Multi-day use pod systems need ~ 18 AHR rechargeable batteries ($40)
- Will need power management components to use solar cells/batteries ($60)
- Consider using land power if at all possible (higher data collection rates)

General Research Discovery Findings

Selection of Complete or Component PM Sensors

- Cost range from $25 to $2500 for the "low cost variety"
- Component variety requires expertise in <u>engineering</u> (power integration/data processing/data storage)
- R^2 versus reference monitors widely variable (0.01 to ~ 0.8) in field evaluations
- Chamber tests do not replicate results under ambient conditions
- Light scattering particle detection from ~ 0.3 μm to 17 μm
- Most have no direct size fractionation options

Selection of Gas Phase Sensors O_3, NO_2, SO_2, CO

- Component (~$50 to $300) to Complete Pod systems ($1500-$10K) exist
- O_3 sensors (~ $50-$1500) have shown excellent reference agreement ($R^2 > 0.9$); Detection limit = ~5 ppb
- NO_2 sensors (~$50-$1500) co-responsive with O_3 and must be resolved ($R^2 > 0.8$); Detection limit = ~5 ppb
- SO_2 sensors (~$50-$1500) have poorest limits of detection being reported (~50 ppb). Little improvement observed during 2012 to present
- CO sensors (~$100-$2500) have difficulty with <5 ppm measurements and temperature changes

General Research Discovery Findings

Selection of Meteorological Sensors

- Components (~$30 to $1500)
- Ultrasonic, vane and cup designs are options
- RH and temp are must have data collections
- Ensure RH and temp sensors collect ambient conditions
- Low cost varieties often highly agree with reference monitors (R^2>0.9)

Air Toxics and Other Sensors of Interest

- Cost range from $50->$2000
- IH-type offer good general performance as survey devices
- Most VOC sensors are of the total VOC variety (Photoionization Detection)
- Limits of detection in the range of 5-20 ppb have been reported
- Low cost sensors reporting VOC "specificity" have not been realized
- Awaiting nano-technology and other emerging sensing elements to reach the market

EPA

Discovery-Summary

- Low cost sensors dominate the commercial market (<$2500) relative to sheer numbers
- Relatively few "sensing elements" actually exist. Many manufacturers using same elements
- Greater availability of different PM sensors versus gas phase sensors (brands)
- Gas phase sensors dominated by electrochemical and metal oxide varieties
- Data output often driven by ease of use concepts (cloud, android, WiFi). Output requirements often complicates use by professionals
- No industry standardization as to data output format, data processing, or calibration of response functions

Sensor Technology-A Call to Evaluate

- **There was a recognized lack of summarized (peer-acceptable) findings on sensor performance**
- **Manufacturers often provide little technical specification on sensor capabilities**
- **The lack of knowledge was impacting the use of these emerging technologies by a wide range of stakeholders (citizens, regulatory officials, professionals, academics)**
- **The Emerging Technologies research program was positioned to be a leader in this research need**

atmosphere MDPI

Review

Interpreting Mobile and Handheld Air Sensor Readings in Relation to Air Quality Standards and Health Effect Reference Values: Tackling the Challenges

George M. Woodall [1,*], Mark D. Hoover [2], Ronald Williams [1], Kristen Benedict [1], Martin Harper [2,†], Jhy-Charm Soo [2], Annie M. Jarabek [1], Michael J. Stewart [1], James S. Brown [1], Janis E. Hulla [3], Motria Caudill [4], Andrea L. Clements [1], Amanda Kaufman [1], Alison J. Parker [5], Martha Keating [1], David Balshaw [6], Kevin Garrahan [7], Laureen Burton [7], Sheila Batka [8], Vijay S. Limaye [8], Pertti J. Hakkinen [9] and Bob Thompson [1]

[1] Environmental Protection Agency, Research Triangle Park, NC 27711, USA; williams.ronald@epa.gov (R.W.); benedict.kristen@epa.gov (K.B.); jarabek.annie@epa.gov (A.M.J.); stewart.michael@epa.gov (M.J.S.); brown.james@epa.gov (J.S.B.); clements.andrea@epa.gov (A.L.C.); kaufman.amanda@epa.gov (A.K.); keating.martha@epa.gov (M.K.); thompson.bob@epa.gov (B.T.)
[2] National Institute for Occupational Safety and Health, Morgantown, WV 26505, USA; mhoover1@cdc.gov (M.D.H.); mharper@zefon.com (M.H.); jsoo@cdc.gov (J.-C.S.)
[3] Army Corps of Engineers, Sacramento, CA 95814, USA; janis.e.hulla@usace.army.mil
[4] Agency for Toxic Substances and Disease Registry, Atlanta, GA 30329, USA; caudill.motria@epa.gov
[5] ORISE Fellow hosted by U.S. Environmental Protection Agency, Washington, DC 20004, USA; parker.alison@epa.gov
[6] National Institute for Environmental Health Sciences, Research Triangle Park, NC 27709, USA; balshaw@niehs.nih.gov
[7] Environmental Protection Agency, Washington, DC 20004, USA; garrahan.kevin@epa.gov (K.G.); burton.laureen@epa.gov (L.B.)
[8] Environmental Protection Agency, Chicago, IL 60605, USA; batka.sheila@epa.gov (S.B.); limaye.vijay@epa.gov (V.S.L.)
[9] National Library of Medicine, Bethesda, MD 20892, USA; hakkinenp@mail.nlm.nih.gov
* Correspondence: woodall.george@epa.gov; Tel.: +1-919-541-3896
† Retired. Current affiliation with Zefon International, Inc., Ocala, FL 34474, USA.

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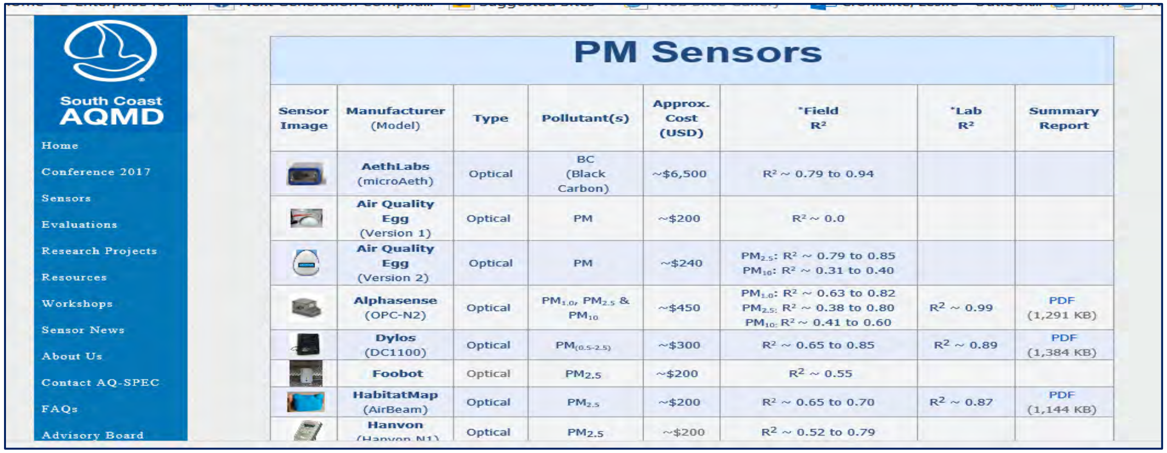
Abstract: The US Environmental Protection Agency (EPA) and other federal agencies face a number of challenges in interpreting and reconciling short-duration (seconds to minutes) readings from mobile and handheld air sensors with the longer duration averages (hours to days) associated with the National Ambient Air Quality Standards (NAAQS) for the criteria pollutants-particulate matter (PM), ozone, carbon monoxide, lead, nitrogen oxides, and sulfur oxides. Similar issues are equally relevant to the hazardous air pollutants (HAPs) where chemical-specific health effect reference values are the best indicators of exposure limits; values which are often based on a lifetime of continuous exposure. A multi-agency, staff-level Air Sensors Health Group (ASHG) was convened in 2013. ASHG represents a multi-institutional collaboration of Federal agencies devoted to discovery and discussion of sensor technologies, interpretation of sensor data, defining the state of sensor-related science across each institution, and provides consultation on how sensors might effectively be used to meet a wide range of research and decision support needs. ASHG focuses on several fronts: improving the understanding of what hand-held sensor technologies may be able to deliver; communicating what hand-held sensor readings can provide to a number of audiences; the challenges of how to integrate data generated by multiple entities using new and unproven technologies; and defining best practices in communicating health-related messages to various audiences. This review summarizes the challenges, successes, and promising tools of those initial ASHG efforts and Federal agency progress on crafting similar products for use with other NAAQS

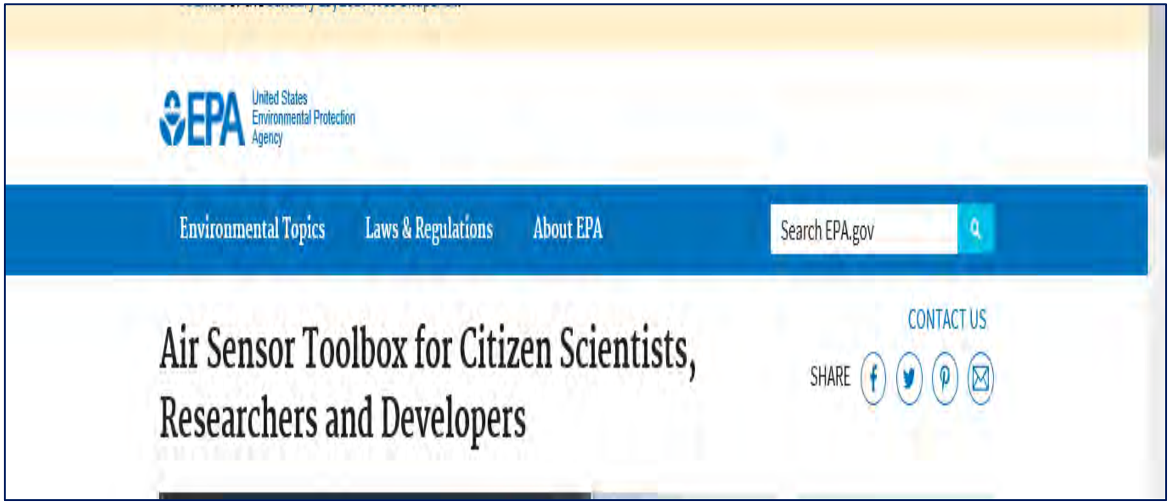
Current US-Based Evaluation Labs

- AQ-SPEC
- U.S. EPA



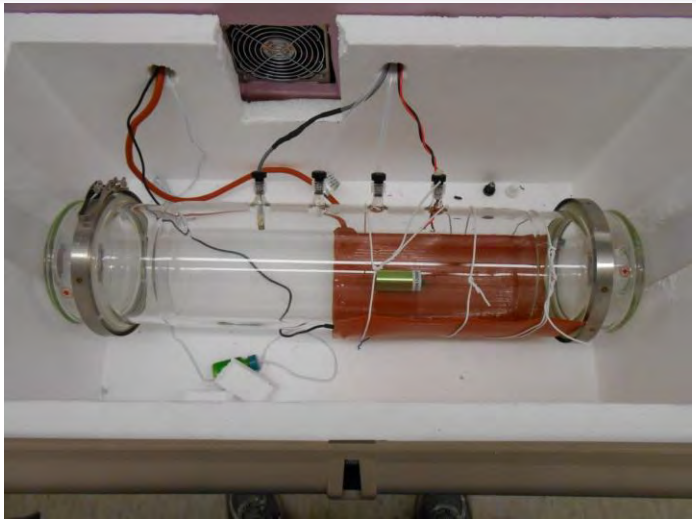
PM Sensors

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	$PM_{(0.5-2.5)}$	~$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		



Sensor Evaluation-Approach

Direct chamber testing of select gas phase low cost sensors



Collocation of select gas and particulate matter sensors with reference monitors

CAIRSENSE-Atlanta


Atmos. Meas. Tech., 9, 5281–5292, 2016
www.atmos-meas-tech.net/9/5281/2016/
doi:10.5194/amt-9-5281-2016

Atmospheric Measurement Techniques
EGU

Community Air Sensor Network (CAIRSENSE) project: evaluation of low-cost sensor performance in a suburban environment in the southeastern United States

Wan Jiao[1], Gayle Hagler[1], Ronald Williams[1], Robert Sharpe[2], Ryan Brown[3], Daniel Garver[3], Robert Judge[4], Motria Caudill[5], Joshua Rickard[6], Michael Davis[7], Lewis Weinstock[8], Susan Zimmer-Dauphinee[9], and Ken Buckley[9]

[1]US Environmental Protection Agency (EPA), Office of Research and Development, Research Triangle Park, NC 27711, USA
[2]ARCADIS US, Inc., Durham, NC 27713, USA
[3]US EPA, Region 4, Atlanta, GA 30303, USA
[4]US EPA, Region 1, Boston, MA 02109, USA
[5]US EPA, Region 5, Chicago, IL 60604, USA
[6]US EPA, Region 8, Denver, CO 80202, USA
[7]US EPA, Region 7, Lenexa, KS 66219, USA
[8]US EPA, Office of Air Quality Planning and Standards, Research Triangle Park, NC 27711, USA
[9]Georgia Environmental Protection Division, Atlanta, GA 30354, USA

Correspondence to: Gayle Hagler (hagler.gayle@epa.gov)

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Abstract. Advances in air pollution sensor technology have enabled the development of small and low-cost systems to measure outdoor air pollution. The deployment of a large number of sensors across a small geographic area would have potential benefits to supplement traditional monitoring networks with additional geographic and temporal measurement resolution, if the data quality were sufficient. To understand the capability of emerging air sensor technology, the Community Air Sensor Network (CAIRSENSE) project deployed low-cost, continuous, and commercially available air pollution sensors at a regulatory air monitoring site and as a local sensor network over a surrounding ~2 km area in the southeastern United States. Collocation of sensors measuring oxides of nitrogen, ozone, carbon monoxide, sulfur dioxide, and particles revealed highly variable performance, both in terms of comparison to a reference monitor as well as the degree to which multiple identical sensors produced the same signal. Multiple ozone, nitrogen dioxide, and carbon monoxide sensors revealed low to very high correlation with a reference monitor, with Pearson sample correlation coefficient (r) ranging from 0.39 to 0.97, −0.25 to 0.76, and −0.40 to 0.82, respectively. The only sulfur dioxide sensor tested revealed no correlation ($r < 0.5$) with a reference monitor and erroneously high concentration values. A wide variety of particulate matter (PM) sensors were tested with variable results – some sensors had very high agreement (e.g., $r = 0.99$) between identical sensors but moderate agreement with a reference $PM_{2.5}$ monitor (e.g., $r = 0.65$). For select sensors that had moderate to strong correlation with reference monitors ($r > 0.5$), step-wise multiple linear regression was performed to determine if ambient temperature, relative humidity (RH), or age of the sensor in number of sampling days could be used in a correction algorithm to improve the agreement. Maximum improvement in agreement with a reference, incorporating all factors, was observed for an NO_2 sensor (multiple correlation coefficient $R^2_{adj\text{-}orig} = 0.57$, $R^2_{adj\text{-}final} = 0.81$); however, other sensors showed no apparent improvement in agreement. A four-node sensor network was successfully able to capture ozone (two nodes) and PM (four nodes) data for an 8-month period of time and show expected diurnal concentration patterns, as well as potential ozone titration due to nearby traffic emissions. Overall, this study demonstrates the performance of emerging air quality sensor technologies in a real-world setting; the variable agreement between sensors and reference monitors indicates

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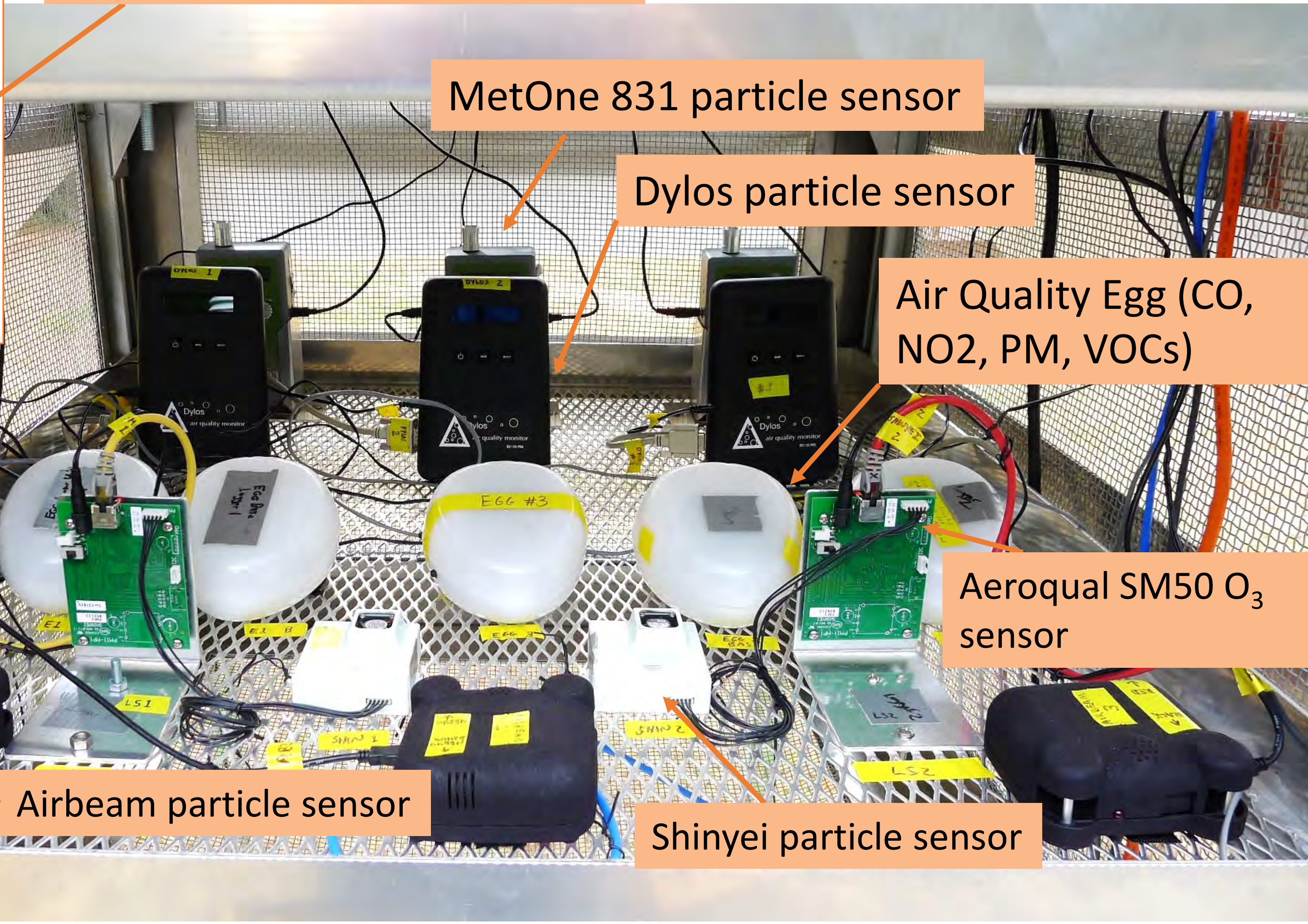
Atlanta and Denver- Climate Extremes

Opportunity to examine highly varying RH and temperature impacts upon sensor performance versus state-operated regulatory monitoring platforms

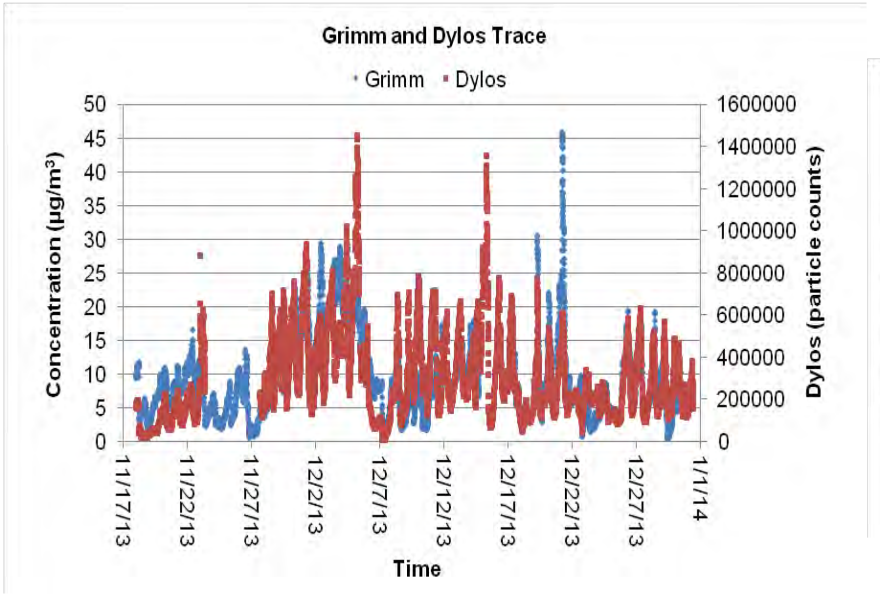
CAIRSENSE-Denver Monitoring Site

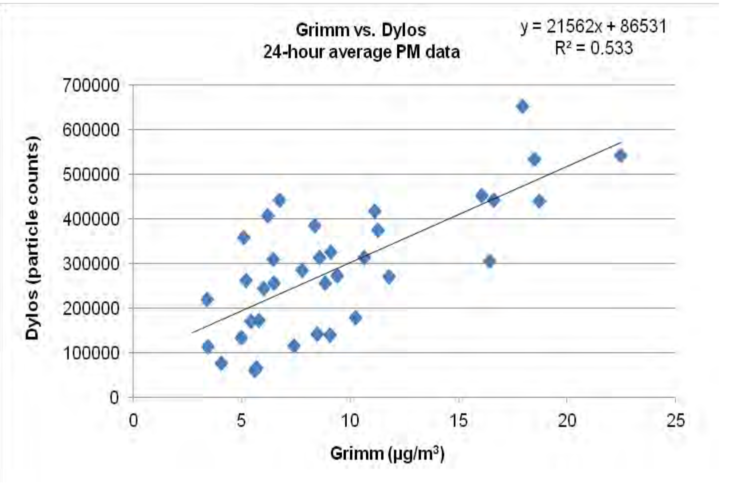
Atlanta Testing

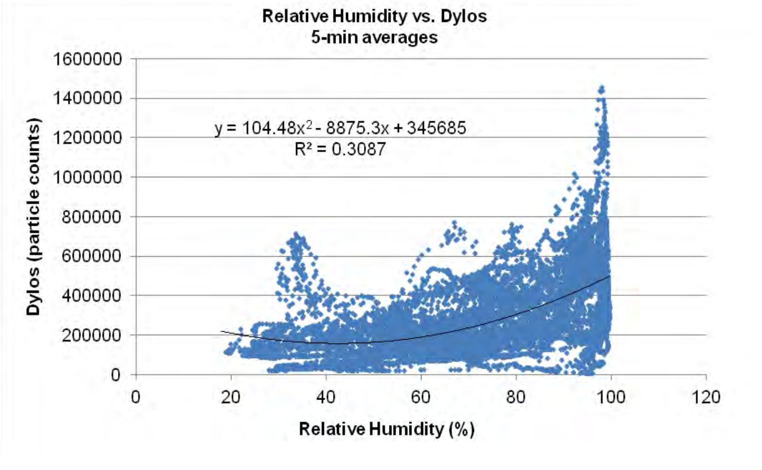


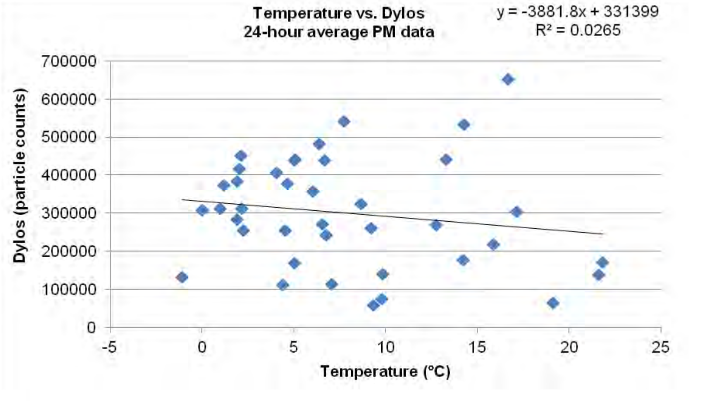
Not shown: Cairpol NO_2/O_3 sensor

An Example of In-Depth PM Sensor Evaluation

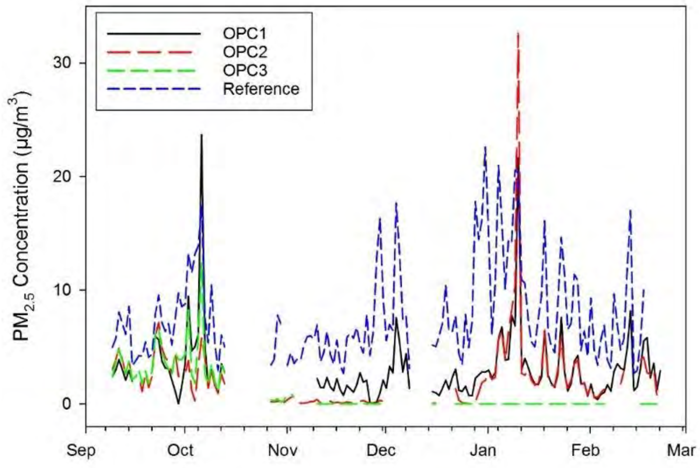


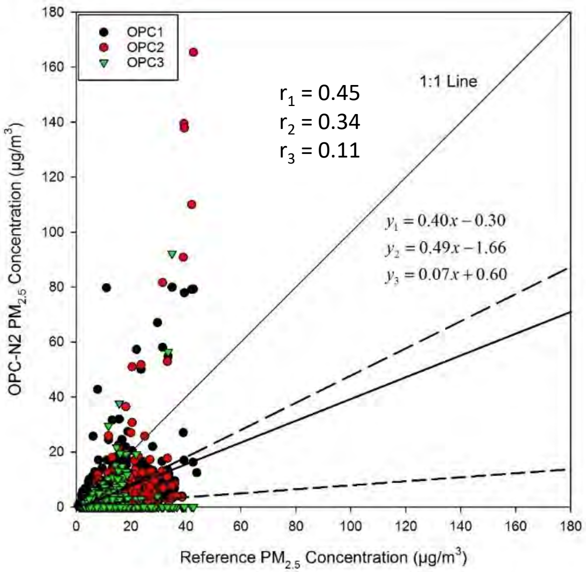






An Example: OPC-N2 $PM_{2.5}$





- Unit 3 failed in in November
- Units 1 and 2 agree except during Nov-Dec
- Suspect assignment to size bins by manufacturer is mostly an estimation

Hourly Average PM Correlations

	AirAssure1	AirAssure2	AirAssure3	Airbeam1	Airbeam2	Airbeam3	DylosF1	DylosF2	DylosF3	OPCF1	OPCF2	OPCF3	Speck1	Speck2	Speck3	Shinyei1	Shinyei2	Shinyei3	TZOA1	TZOA2	TZOA3	Regulatory
AirAssure1	100																					
AirAssure2	98	100																				
AirAssure3	98	98	100																			
Airbeam1	91	90	91	100																		
Airbeam2	90	89	90	100	100																	
Airbeam3	90	88	89	100	100	100																
DylosF1	83	81	82	78	83	82	100															
DylosF2	88	84	85	92	96	96	85	100														
DylosF3	87	84	84	94	95	96	84	99	100													
OPCF1	65	65	66	62	50	48	64	52	46	100												
OPCF2	57	58	59	48	55	53	84	57	58	62	100											
OPCF3	32	37	38	39	-2	-2	9	13	0	39	10	100										
Speck1	22	29	32	21	28	25	20	4	2	26	17	27	100									
Speck2	29	35	39	22	21	18	25	4	3	31	21	30	77	100								
Speck3	24	32	36	20	18	16	20	-2	-4	27	21	33	84	92	100							
Shinyei1	86	88	91	84	81	80	76	68	68	74	62	56	43	54	52	100						
Shinyei2	76	80	83	70	71	69	77	57	56	67	68	20	57	67	68	93	100					
Shinyei3	13	13	12	14	80	82	13	11	12	11	9	10	12	7	11	19	18	100				
TZOA1	10	12	12	27	8	8	2	4	-5	18	22	28	3	-16	6	7	-3	-3	100			
TZOA2	58	59	60	69	92	91	67	66	76	21	30	23	17	23	25	57	62	9	8	100		
TZOA3	65	65	66	71	93	92	69	71	80	21	25	18	16	22	20	54	60	3	4	93	100	
Regulatory	80	78	81	82	84	82	86	78	73	45	34	11	24	40	35	71	72	1	12	66	72	100

AirAssure Airbeam Dylos OPC Speck Shinyei TZOA

- Most sensors exhibit strong correlation within model types
- Correlations with regulatory monitors range from weak to very strong
- Hourly average values had strongest correlations

EPA Citizen Science Air Monitor (CSAM) Laboratory Evaluation at AQ-SPEC Facilities

Southern California- Field Collocation

Sensor Collocation

Pod versus GRIMM Field Comparison

R^2	FEM GRIMM	Unit 401	Unit 402	Unit 403	Unit 404	Unit 406	Unit 407	Unit 408	Unit 409	Unit 410
FEM GRIMM	1									
Unit 401	0.0008	1								
Unit 402	0.5488	0.0002	1							
Unit 403	0.5138	0.0007	0.9831	1						
Unit 404	0.2356	0.0676	0.9655	0.9815	1					
Unit 406	0.5247	0.0010	0.9775	0.9945	0.9827	1				
Unit 407	0.5039	0.0001	0.9820	0.9931	0.9806	0.994	1			
Unit 408	0.4644	0.0004	0.9736	0.9708	0.9583	0.961	0.972	1		
Unit 409	0.4551	0.0001	0.9739	0.9783	0.9587	0.971	0.979	0.989	1	
Unit 410	0.5098	0.0001	0.9857	0.9762	0.9669	0.968	0.976	0.991	0.989	1

United Nations Pod Evaluation

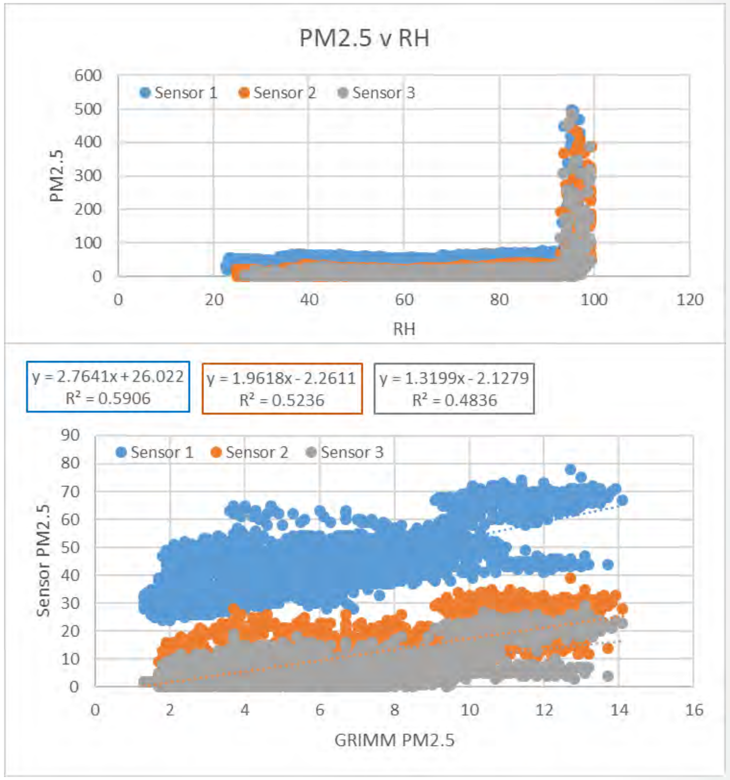
- Conducted an evaluation of a UN designed sensor prototype
- Sensor was compared versus reference monitors for a 30 day period
- Test results were instrumental in UN decision to make significant changes to original design

Sensor Evaluation – Current Testing

- Objectives:
  - Evaluate the performance of a number of low-cost air sensors via collocation with reference instruments at the AIRS platform in RTP, NC.
  - Develop materials to communicate the evaluation results to the public.
- Status:
  - Seven sensors selected for evaluations
    - TES-5322 and Plantower PMS 7003 Particulate Matter (PM) sensors were collocated at AIRS Nov. – Dec. 2017. Performance characterization summary is ongoing.
    - Caripol and Aeroqual NO_2 sensors were collocated at AIRS between Nov. 2017 and Jan. 2018. Performance characterization is ongoing.
    - Evaluation of the Purple Air, Aeroqual, and Vaisala PM sensors is expected to begin in Feb. 2018.

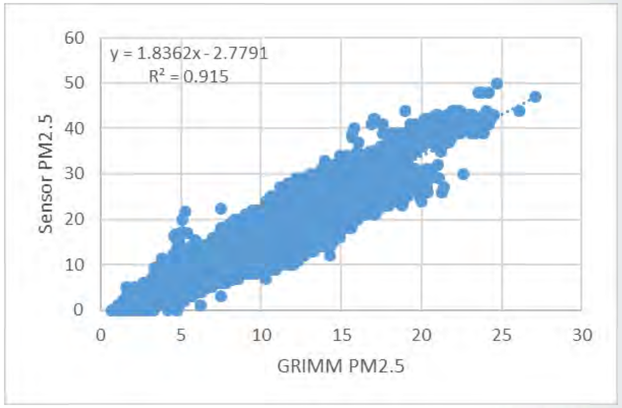
Sensor Evaluation – TES-5322 results

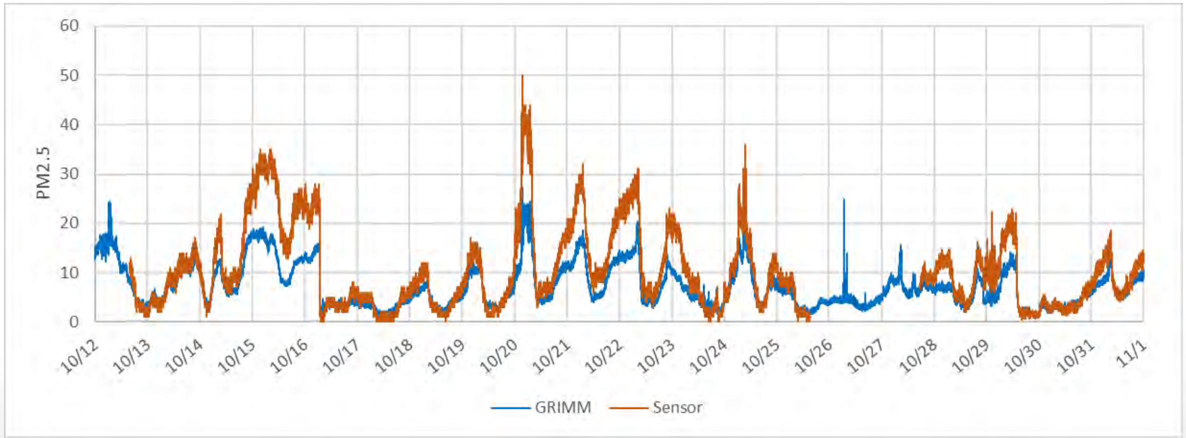
- PM sensor does not perform well in high humidity conditions (>92% RH).
- The PM sensor component must be calibrated prior to use due to large biases (2-30μg/m^3) observed between similar sensors. When compared to one another with high RH data removed, agreement between sensors is reasonable (r^2>0.75).
- When compared with reference instruments, the agreement remains modest (r^2~0.5) and reported concentrations are biased high (30-300%).
- Temperature and humidity sensors agree very well (r^2>0.95) with reference instruments with the temperature sensor reading roughly 10% high.
- The VOC sensor is not sensitive to ambient concentrations.



Sensor Evaluation – Plantower 7003 Results

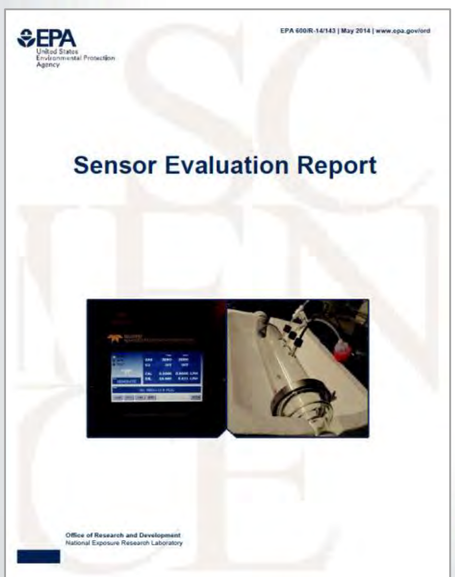
- PM concentrations are highly correlated ($r^2>0.9$) between sensors with no significant bias.
- PM concentrations are highly correlated ($r^2>0.9$) with reference instruments for all size fractions but measure roughly twice the measured reference concentrations.
- No notable temperature or RH influence was observed.

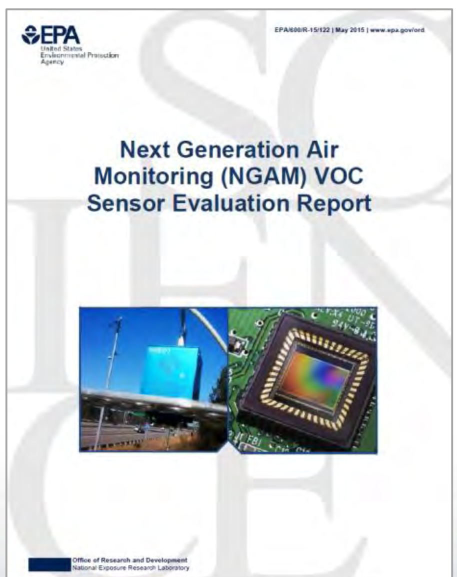


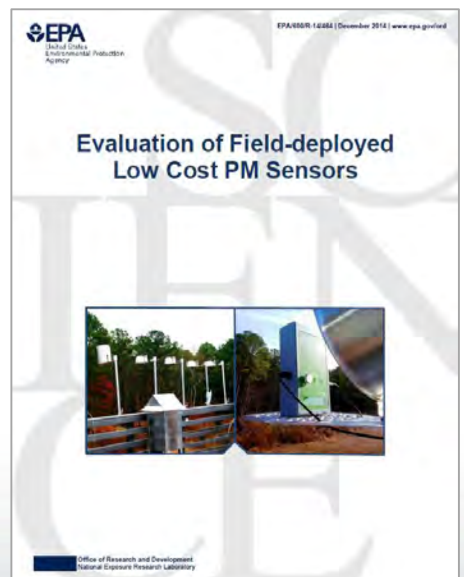


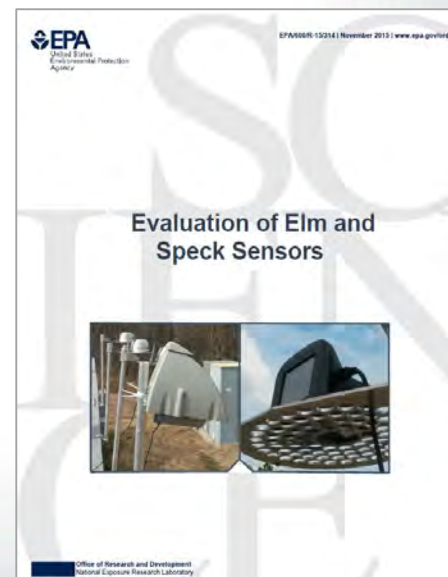
Example: Sensor Evaluation Reports

- Laboratory and field evaluations of select sensors on the market
- Evaluated performance characteristics:
  - R^2 (coefficient of determination) – sensor response compared to FEM/FRM
  - Effect of relative humidity and temperature on sensor response
  - Uptime
  - Ease of operation/installation
  - Mobility









A Call for Application


em • feature

Sensors and 'Apps' for Community-Based Atmospheric Monitoring

by Richard M. White, Igor Paprotny, Frederick Doering, Wayne E. Cascio, Paul A. Solomon, and Lara A. Gundel

Recent advances in both sensors and wireless communication provide opportunities for improved exposure assessment and increasing community involvement in reducing levels of human exposure to airborne contaminants. These new technologies can enhance data collection to answer science and policy questions related to the health and environmental effects of air pollution.[1]

Richard M. White and Igor Paprotny are both with the Electrical Engineering and Computer Sciences Department, University of California, Berkeley, CA, and the Berkeley Sensor & Actuator Center; Frederick Doering is with the Mechanical Engineering Department, University of California, Berkeley, CA, and the Berkeley Sensor & Actuator Center; Wayne E. Cascio is with the U.S. Environmental Protection Agency's Office of Research and Development, Research Triangle Park, NC; Paul A. Solomon is with the U.S. Environmental Protection Agency's Office of Research and Development, Las Vegas, NV; and Lara A. Gundel is with the Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA. E-mail: rwhite@eecs.berkeley.edu.

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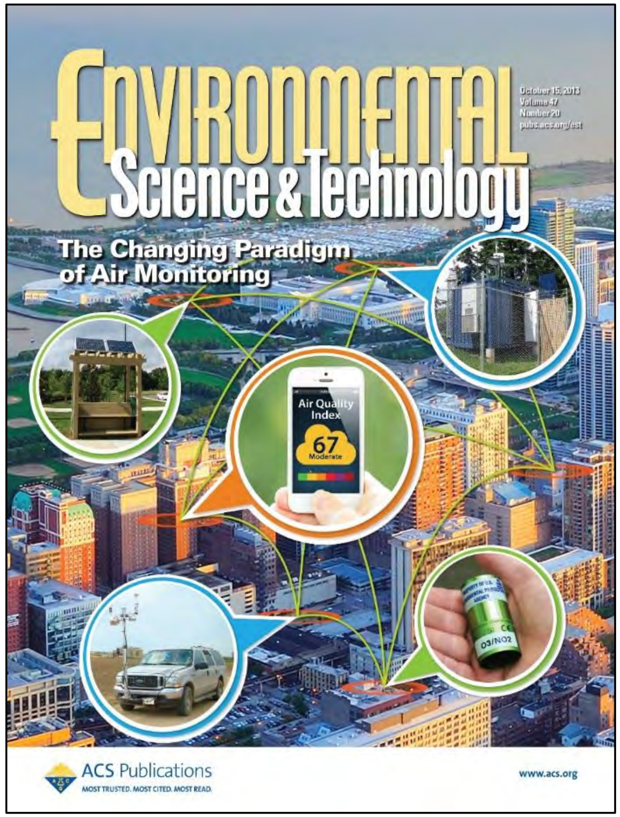
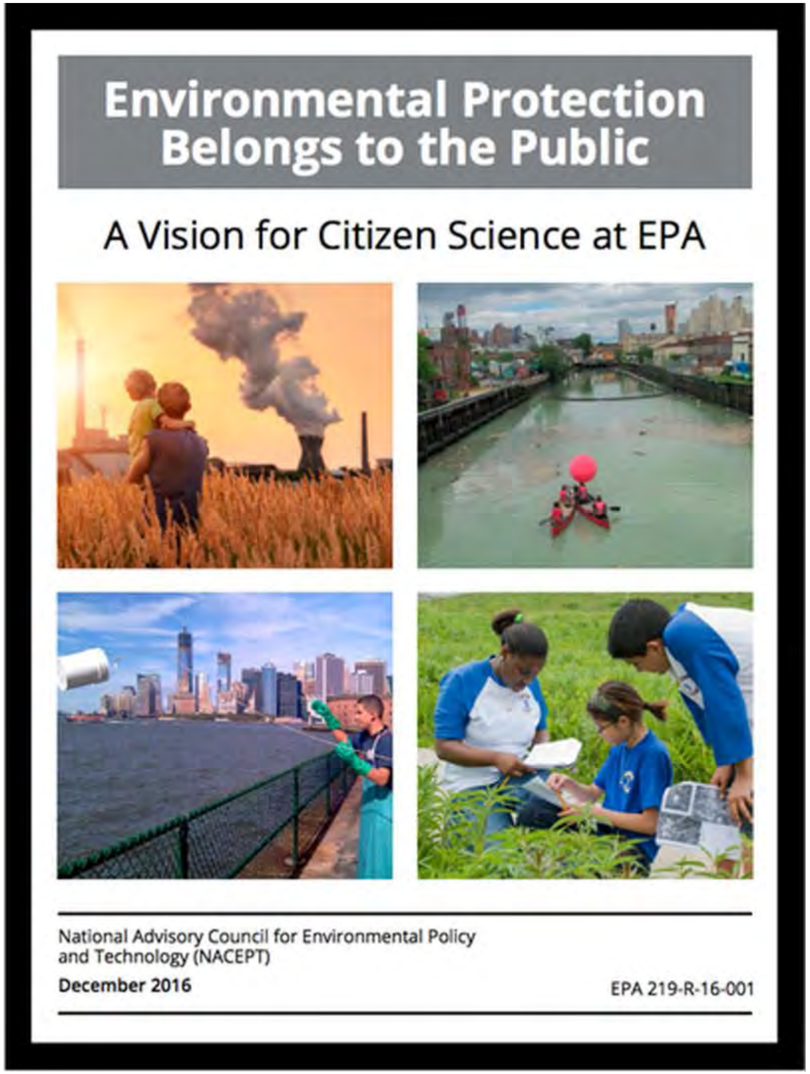


Citizen Science


Environmental Protection Belongs to the Public

A Vision for Citizen Science at EPA

National Advisory Council for Environmental Policy and Technology (NACEPT)

December 2016

EPA 219-R-16-001

National Advisory Council for Environmental Policy and Technology (NACEPT)

"The NACEPT Council's 28 members – representatives of academia, business and industry, nongovernmental organizations, as well as state, local, and tribal governments – ...

..have identified citizen science as an invaluable opportunity for the Agency to strengthen public support for EPA's mission as well as as the best approach for the Agency to connect with the public."

EPA Recognizes Community Interest in Applying Emerging Technologies

- Importance of sensors and how quickly new technologies are advancing and revolutionizing regional, community, fence-line, and personal monitoring. Ongoing or recent research includes:
  - Smart City Challenge-2 communities engaged (Baltimore/Lafayette)
  - Promoting Community Monitoring-Village Green (8 stations)
  - STAR grant program-Six academic/community partnership grants
  - Community-specific research opportunities (Village Green stations)
  - Multiple Region-based Citizen Science projects

Smart City Challenge

Village Green Stations

STAR Community Challenge

Village Green Project

- Prototype located in Durham, NC outside of a public library
- Self-contained system incorporates
  - **power supply**: solar panels & battery
  - **microprocessor**
  - **cellular modem**
- Measures two common air pollutants
  - **ozone** and **fine particulate matter ($PM_{2.5}$, particle diameter ≤ 2.5 µm)**
- Measures **weather**
  - wind speed and direction
  - temperature and humidity
- Sampling rate – **every minute**
- Comparable results
  - Instruments agreed within 10-20 % of reference monitors located nearby
- Prototype design made available: http://pubs.acs.org/doi/suppl/10.1021/acs.est.5b01245

Select Village Green Stations

Partners: City of Philadelphia, National Park Service

Partners: State of Oklahoma, Myriad Botanical Gardens

Partners: State of Kansas, Wyandotte County, School District

Partners: District Department of the Environment, Smithsonian

Latest Village Green Station

Location: Houston, TX
Partners: Region 6 EPA, City of Houston, Medical Science Museum

Total of 8 Village Green stations have been deployed

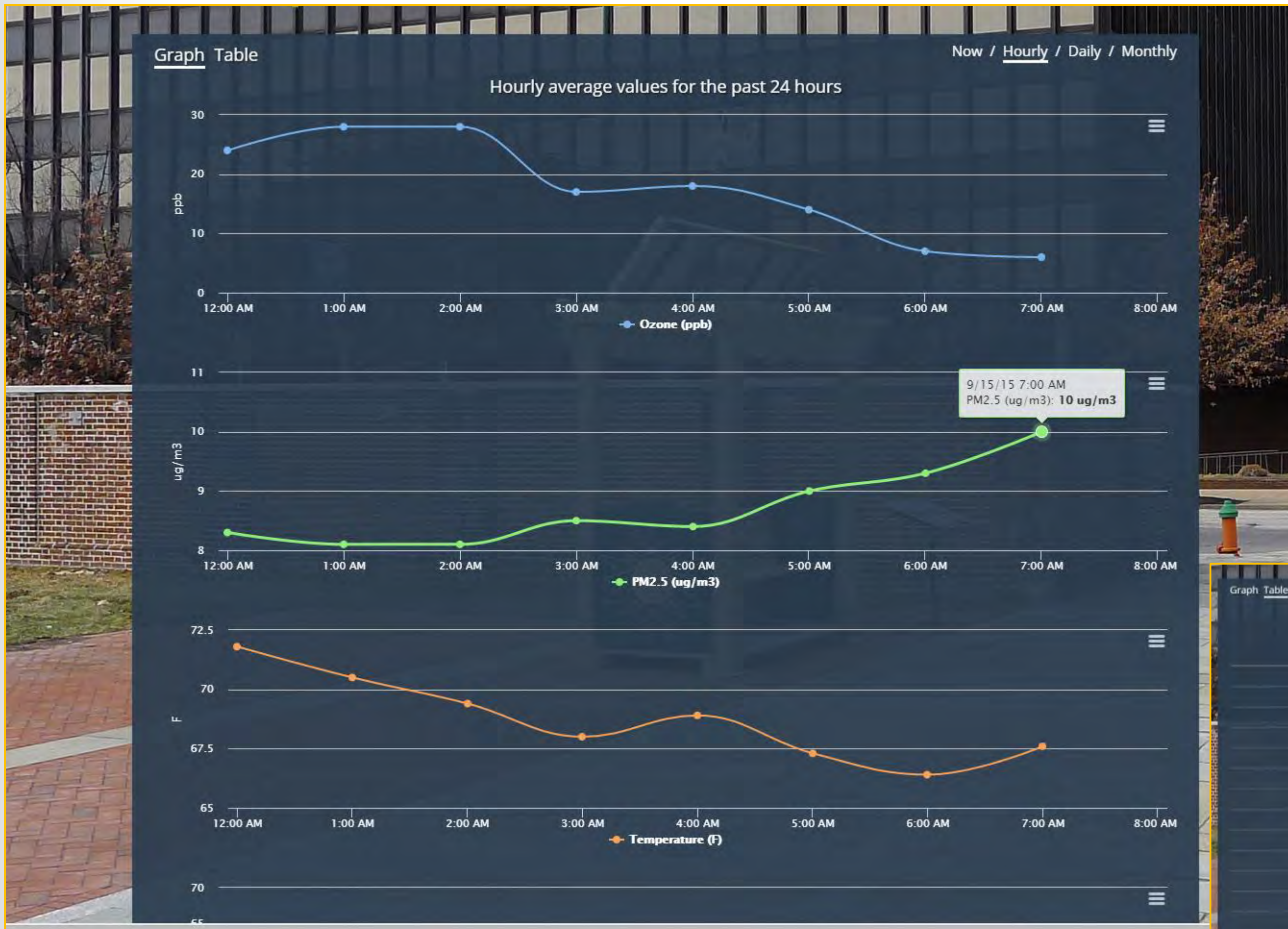
ORD/OAQPS now providing access to historical data sets

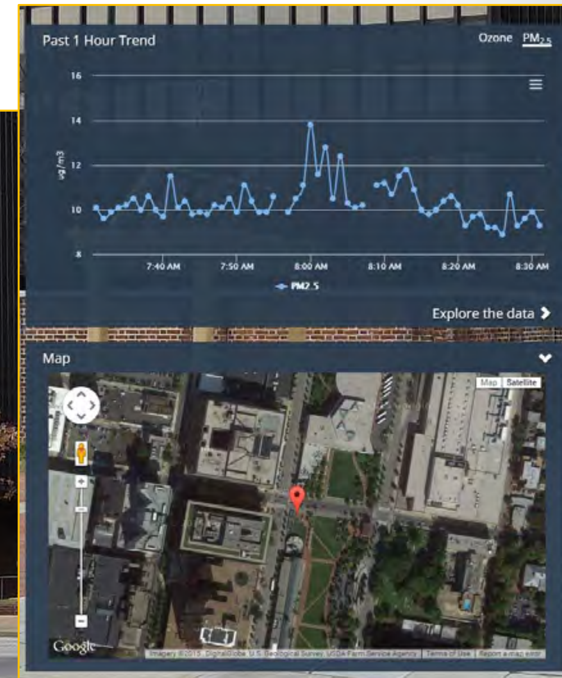
Village Green (The Movie) and operational instructional guide now available

https://www.epa.gov/air research/village-green-project

Village Green Project: Data Website

Data website: Interactive data exploration





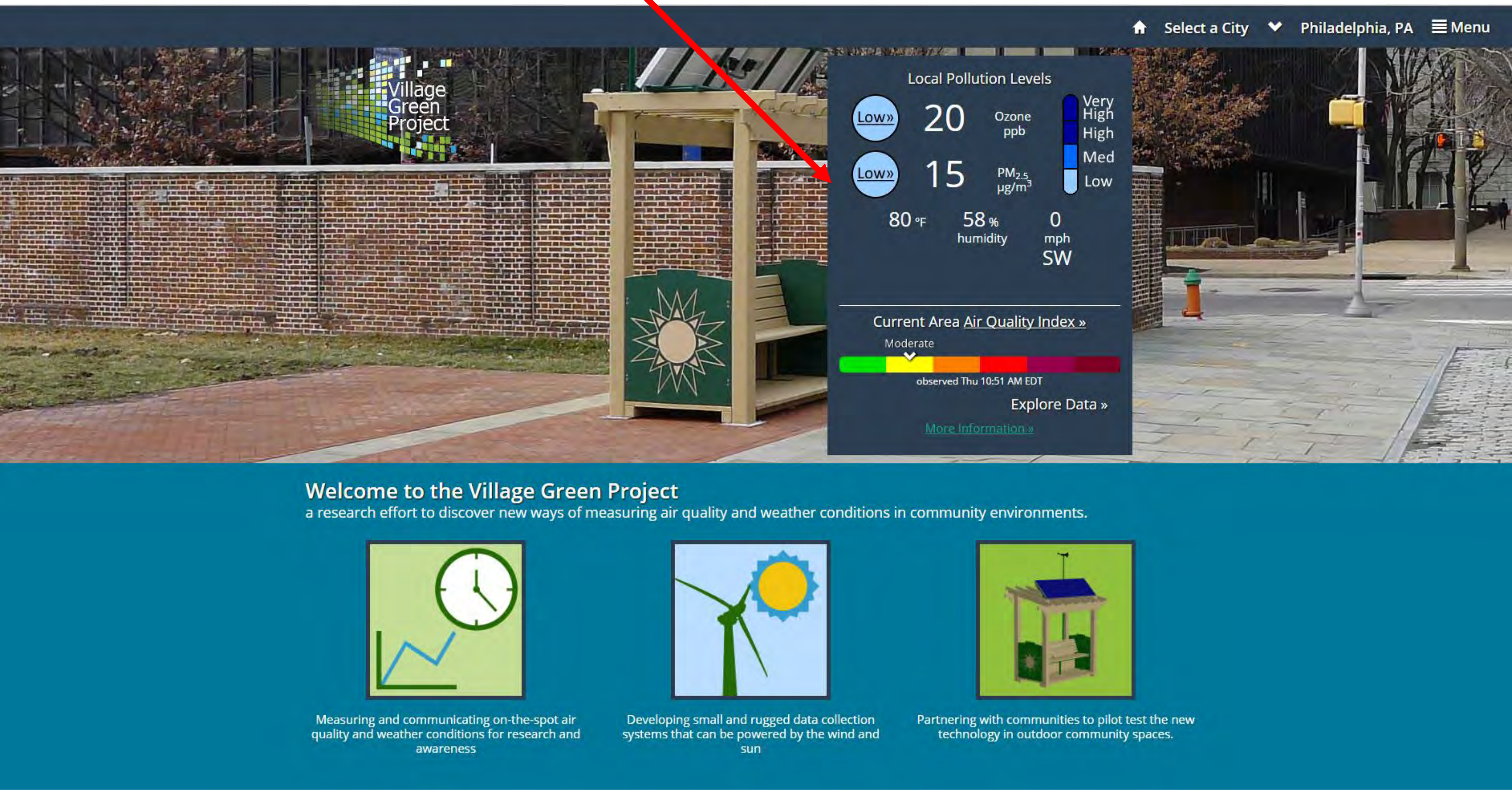

Graph Table

Now / Hourly / Daily / Monthly

Hourly average values for the past 24 hours

Date EDT	O_3 ppb	$PM_{2.5}$ µg/m³	Temp °F	RH %	W Spd mph
9/15 7:00 AM	6	10.0	67.6	61.8	0.7
9/15 6:00 AM	7	9.3	66.4	64.4	0.7
9/15 5:00 AM	14	9.0	67.3	62.0	0.9
9/15 4:00 AM	18	8.4	68.9	57.7	2.5
9/15 3:00 AM	17	8.5	68.0	59.5	1.1
9/15 2:00 AM	28	8.1	69.4	54.4	0.7
9/15 1:00 AM	28	8.1	70.5	52.4	0.7
9/15 12:00 AM	24	8.3	71.8	49.3	1.1
9/14 11:00 PM	20	11.7	72.0	48.9	0.7
9/14 10:00 PM	19	8.9	73.0	47.8	0.4
9/14 9:00 PM	21	8.2	75.2	42.8	1.3
9/14 8:00 PM	17	7.6	75.2	41.2	1.1
9/14 7:00 PM	25	7.4	76.5	37.8	0.7
9/14 6:00 PM	31	7.4	78.4	32.1	2.5
9/14 5:00 PM	31	6.8	79.3	30.2	3.4

Village Green Data Messaging Tool



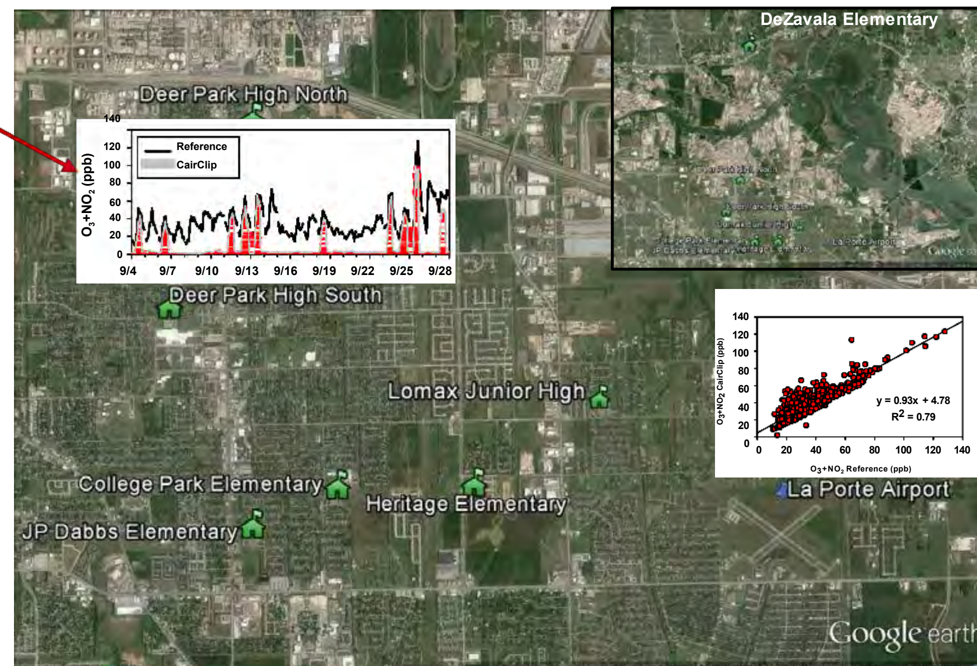
DISCOVER-AQ

Direct partnership with citizen scientists

Houston, Texas Campaign (Sep 2013) and Denver, Colorado Campaign (Jul-Aug 2014)

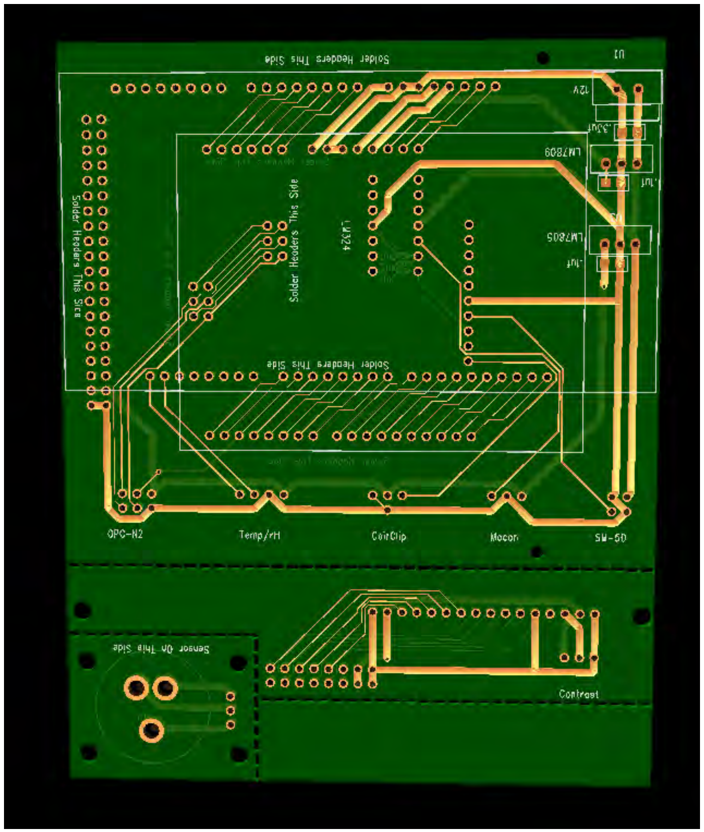
- ***Sensor Evaluation*: Collocated sensors with reference analyzers**
- ***Citizen Science*: sensors operated by local community (schools, colleges/ universities, local residents)**

Houston Citizen Science



Reference: Duvall et al. 2016, Sensors, 2016 [*(http://www.mdpi.com/1424-8220/16/10/1698/html)*](http://www.mdpi.com/1424-8220/16/10/1698/html)

Development of Sensors for Regional Research Application Needs



Emerging Technology Collaborations

Regional Applied Research Effort (RARE) Projects

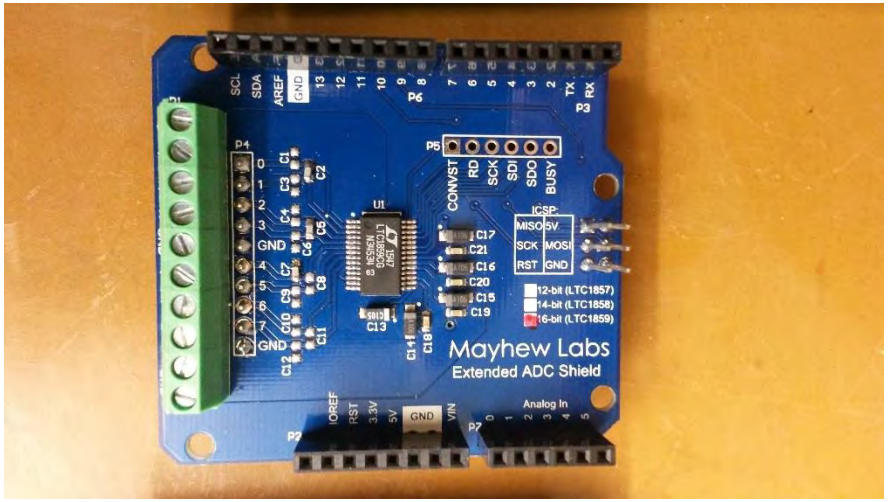
- **Region 2** - Citizen Science Toolbox - Collaboration between ORD/R2/Ironbound Community Corporation to provide Ironbound community with a "Toolbox" appropriate for initiating a community-based, participatory environmental monitoring study

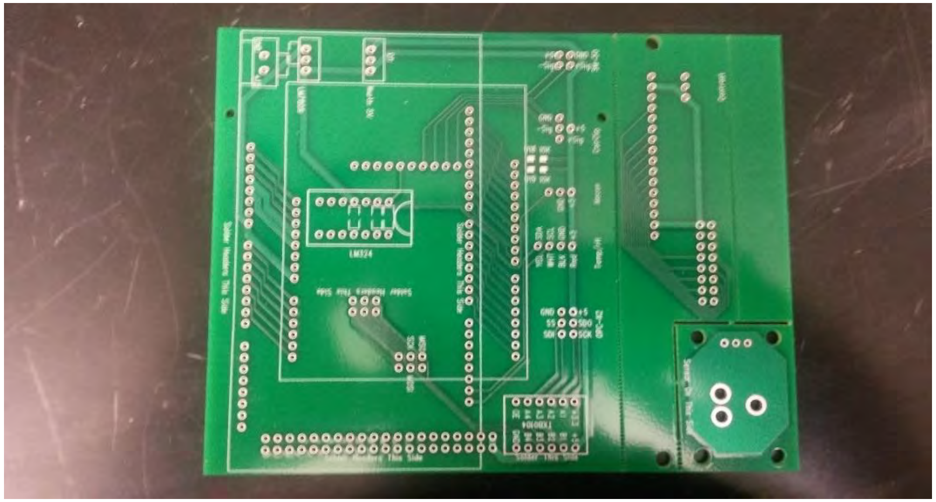
- **Regions 5, 10** - Application of lower cost air monitoring technologies (AirMapper) for local-scale air quality investigation

- **Region 2 (Puerto Rico) -** Efficacy of Citizen Science Air Monitoring for Building Awareness of Exposures for Citizens in a U.S. Caribbean Urban Neighborhood Impacted by Heavy Industrial Contamination

- **Region 7 (Kansas City)** - Regional science project with citizen scientists collecting data using the AirMapper sensor

Sensor Pod Development





United States Environmental Protection Agency

EPA/600/R-16/049 | May 2016 | www.epa.gov/ord

Citizen Science Air Monitoring in the Ironbound Community

Office of Research and Development
National Exposure Research Laboratory

ENV-2016-0044-ver9-Kaufman_1P
Type: other

ENVIRONMENTAL JUSTICE
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DOI: 10.1089/env.2016.0044

Original Article

A Citizen Science and Government Collaboration: Developing Tools to Facilitate Community Air Monitoring

AU1 ► Amanda Kaufman, Ron Williams, Timothy Barzyk, Molly Greenberg, Marie O'Shea, Patricia Sheridan, Anhthu Hoang, Christine Ash, Avraham Teitz, Mustafa Mustafa, and Sam Garvey

ABSTRACT

The U.S. Environmental Protection Agency (EPA) is actively involved in supporting citizen science projects and providing communities with information and assistance for conducting their own air pollution monitoring. As part of a Regional Applied Research Effort (RARE) project, EPA's Office of Research and Development (ORD) worked collaboratively with EPA Region 2 and the Ironbound Community Corporation (ICC) in Newark, New Jersey, to develop and test the "Air Sensor Toolbox for Citizen Scientists." In this collaboration, citizen scientists measured local gaseous and particulate air pollution levels by using a customized low-cost sensor pod designed and fabricated by EPA. This citizen science air quality measurement project provided an excellent opportunity for EPA to evaluate and improve the Toolbox resources available to communities. The Air Sensor Toolbox, developed in coordination with the ICC, can serve as a template for communities across the country to use in developing their own air pollution monitoring programs in areas where air pollution is a concern. This pilot project provided an opportunity for a highly motivated citizen science organization and the EPA to work together directly to address environmental concerns within the community. Useful lessons were learned about how to improve coordination between the government and communities and the types of tools and technologies needed for conducting an effective citizen science project that can be applied to future efforts.

Keywords: citizen science, air pollution monitoring, air sensors, community engagement

INTRODUCTION

THE U.S. ENVIRONMENTAL Protection Agency (EPA) facilitates identification of potential environmental concerns by citizen scientists, particularly in vulnerable communities, as part of its mission to protect human health and the environment. The EPA efforts to promote citizen science projects have been largely driven by the general public's strong interest in collecting environmental data that are of importance to their families and communities.[1] ◄AU4

AU2 ► AU3 ► Amanda Kaufman at National Exposure Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. Ron Williams at National Exposure Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. Timothy Barzyk at National Exposure Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. Molly Greenberg at Ironbound Community Corporation, Newark, New Jersey. Marie O'Shea at U.S. Environmental Protection Agency, New York, New York. Patricia Sheridan at U.S. Environmental Protection Agency, New York, New York. Anhthu Hoang at U.S. Environmental Protection Agency, New York, New York. Christine Ash at U.S. Environmental Protection Agency, New York, New York. Avraham Teitz at U.S. Environmental Protection Agency, Edison, New Jersey. Mustafa Mustafa at U.S. Environmental Protection Agency, Edison, New Jersey. Sam Garvey at Jacobs Technology Incorporated, MD-E367, Research Triangle Park, North Carolina.

[1] Duncan C. McKinley, Abraham J. Miller-Rushing, Heidi L. Ballard, Rick Bonney, Hutch Brown, Daniel M. Evans, Rebecca A. French, Julia K. Parrish, Tina B. Phillips, Sean F. Ryan, Lea A. Shanley, Jennifer L. Shirk, Kristine F. Stepenuck, Jake F. Weltzin, Andrea Wiggins, Owen D. Boyle, Russell D. Briggs, Stuart F. Chapin III, David A. Hewitt, Peter W. Preuss, and Michael A. Soukup. "Investing in Citizen Science Can Improve Natural Resource Management and Environmental Protection," *Issues in Ecology* 19 (Fall 2015); J.L. Dickinson and R. Bonney (eds). *Citizen Science: Public Participation in Environmental Research.* (Cornell University Press, 2012).

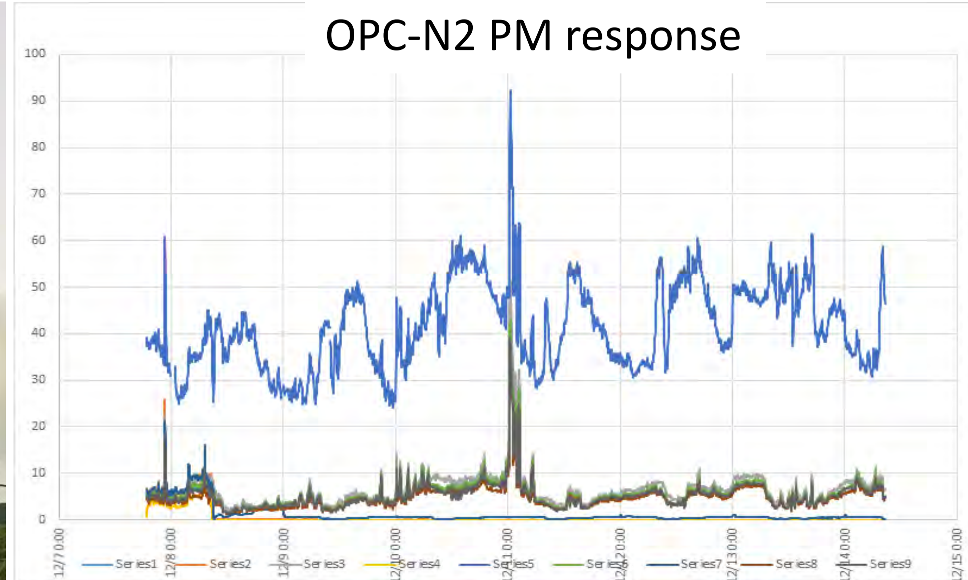
CSAM Technology-Puerto Rico

CSAM and Tripod Support

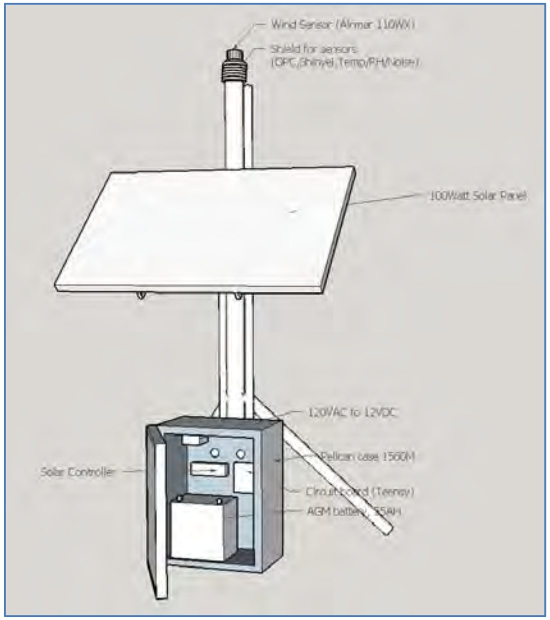
CSAM with sensors and built-in micro-computer

CSAM LED Display

Citizen-Performed Collocation Activity



CitySpace-Memphis



AIRMapper-Educational Awareness Sensor Pod

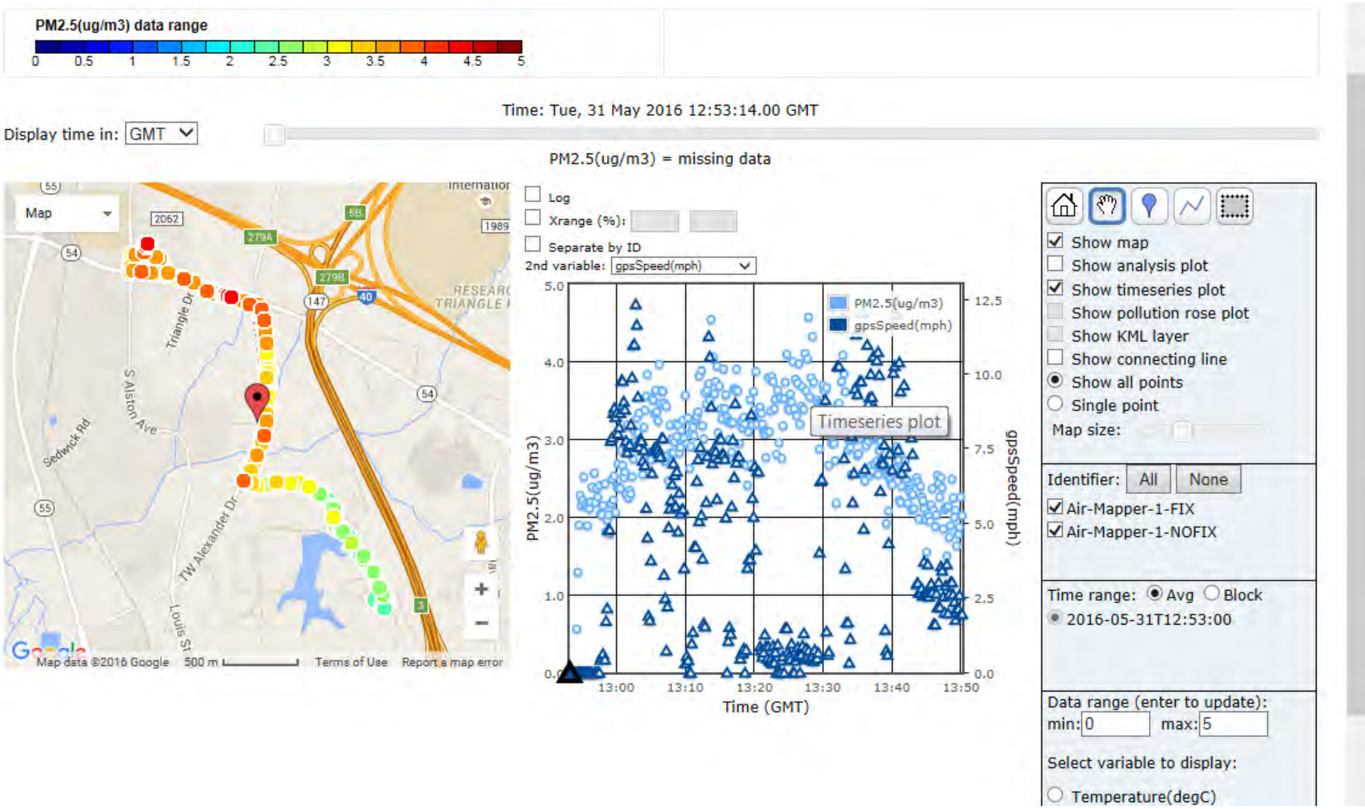
- Easy to use (touch screen based) air quality sensor
- GPS, PM, CO2, RH, temp, noise
- Internal data storage (SD card)
- Data output optimized for integration into RETIGO
- ORD developed for Regions 5, 7, 10 use on various Region-defined projects
- Utilized components selected by ORD to meet technical requirements (cost, weight, etc.)
- Design specifications available if requested (not patented)

Citizen Science Applications

AirMapper: Mobile sensor system

Application- AIRMAPPER with RETIGO

RETIGO- Data visualization and data sharing tool



RETIGO available through www.epa.gov/hesc/real-time-geospatial-data-viewer-retigo

Sensor Loan Project

- Objective: A multi-region RESES project was awarded in FY17 to give Regions the ability to investigate local and regional air quality using lower cost sensors through a sensor pod loan trial. This project will use ORD knowledge and resources to create, characterize, and maintain pods using the best available sensor technologies so that these well characterized and working instruments can be loaned to regional partners who will deploy and collect data in order to investigate a regional air quality issue. This loan arrangement will provide Regions with access to sensor technology while relieving them of some of the technical burdens and upkeep these technologies require. The overall goal from the ORD perspective is to evaluate the practical and technical aspects of a sensor pod loan program.
- Status: Pod development in process

Sensor Loan Project-Phased Execution

FY18 through FY19:

- Design pods, acquire parts, begin build
- Build, test, and calibrate sensor pods in RTP
- Develop SOP and QA/QC procedures for regional QAPPs
- Regions establish relationships with stakeholders (community groups, academic institutions, state agencies, etc.) and develop formal agreements
- Regions use SHC tools to plan sensor deployment placement
- Regions develop QAPPs
- Sensor pod training
- Sensor pod deployments, to be conducted in three sequential phases Sensor pods returned to RTP for calibration/refurbishment – conducted in three phases to follow deployments
- Data Analysis
- Presentation of loan trial/deployment findings
- Project completion

Sensor Collocation Tools

- Training citizen scientists to evaluate sensor performance
  - "Now that community based science, 'citizen scientist', has become more popular, it is nice to have something explain how to collect more viable data using the low-cost sensors because most community members don't consider the accuracy of a sensor compared to a FRM/FEM."
  - *Katie Tiger, Eastern Band of Cherokee Indians*

Citizen volunteers with staff from CAC, EPA, and Mecklenburg County

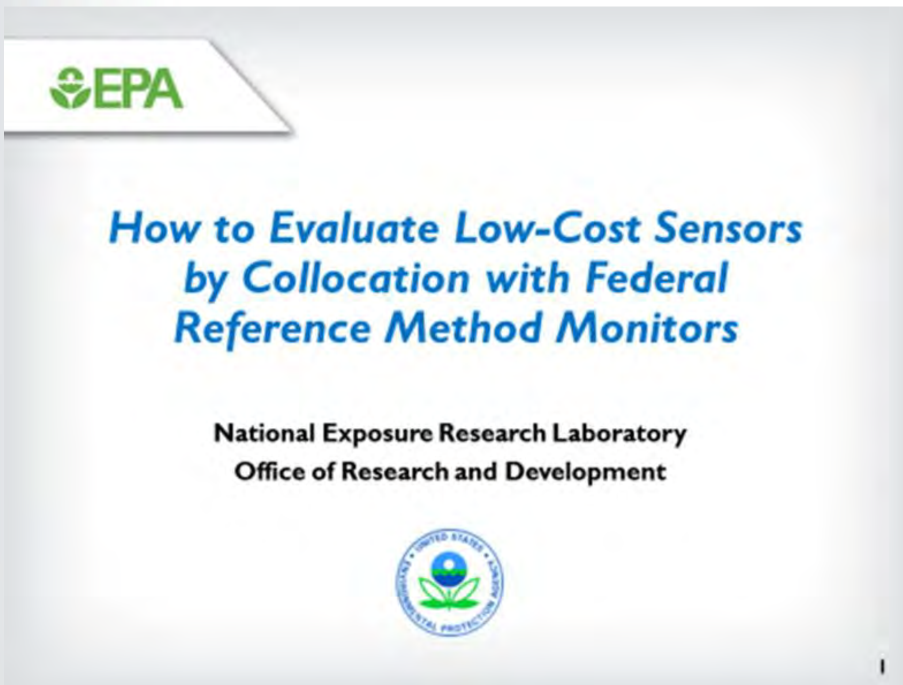
CAC staff and citizen volunteer checking on ozone sensors at deployment site

Particulate matter sensors deployed in triplicate inside weather shelter at EBCI monitoring site

https://www.epa.gov/air-research/instruction-guide-and-macro-analysis-tool-community-led-air-monitoring

EPA-Developed Tools and Guidance

Instruction guide for conducting a successful collocation evaluation of air sensors with regulatory grade instruments, provided as a PowerPoint presentation for easy reading and ample visual tools.

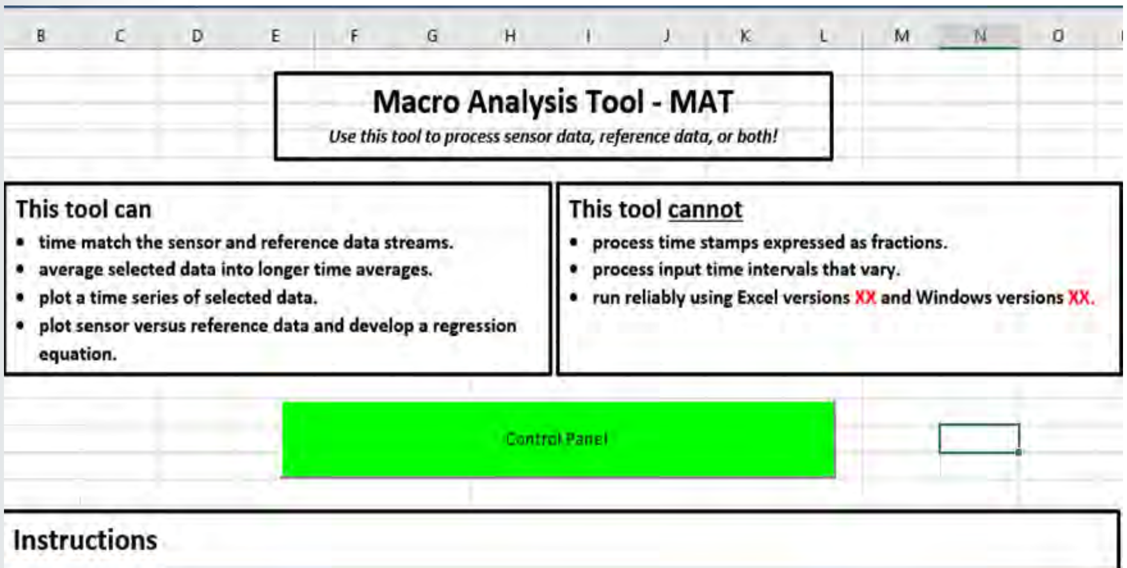


Topics covered:

- Background
- Low-cost sensors vs reference instruments
- Introduction to collocation
- Planning collocation
- Making measurements
- Data recovery and review
- Data comparison
  - **Introduction of Macro Analysis Tool (MAT)**
- Using sensors effectively

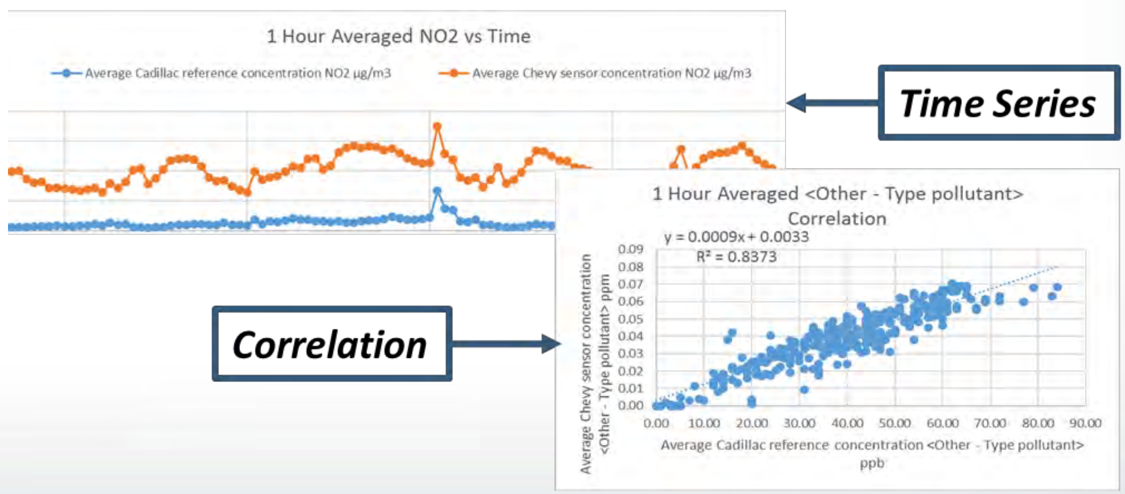
Project partners provided feedback on instruction Guide and MAT, which was used by EPA to improve and finalize these products.

EPA-Developed Tools and Guidance



Easy-to-use spreadsheet based [macro analysis tool](#) for performing data comparisons and interpreting the results. Tool tackles one of the biggest hurdles in citizen-led air monitoring projects – working with the data.

Example Outputs:



Air Sensor Toolbox

- Air Sensor Guidebook
- Technical Evaluation Reports
- Standard Operating Procedures for Air Sensors
- Possible funding opportunities
- Key Links – Community Air Monitoring Training, Air Sensors Workshops, EPA Next Generation Air Monitoring
- Recent Technical Findings – EPA sensor evaluation efforts
- News – articles, blogs, podcasts, videos
- Resources from the Air Quality Sensor Performance Evaluation Center (AQ-SPEC)
- Resources from the European Joint Commission Research Centre

Sensor Related Resources

Air Sensor
Measure · Learn · Share
Citizen Science Toolbox

Contacts:

Ron Williams
919-541-2957
williams.ronald@epa.gov

Amanda Kaufman
919-541-2388
kaufman.amanda@epa.gov

Online Resources Available at:
www2.epa.gov/air-research/air-sensor-toolbox-citizen-scientists

Air Sensor Guidebook

CSAM Operating Procedures

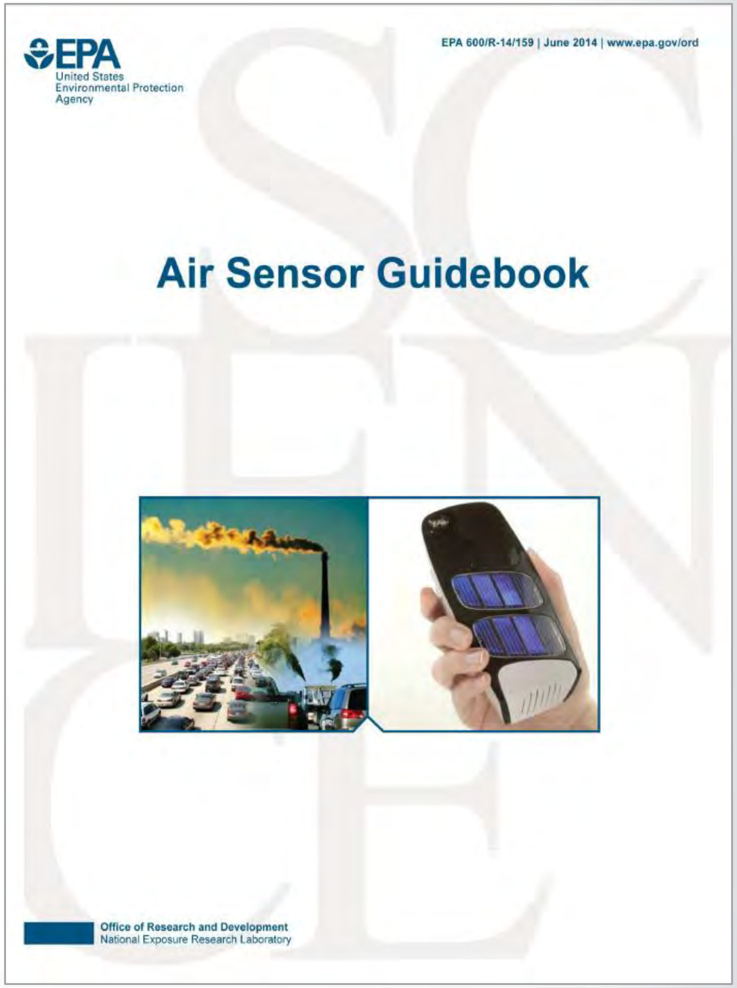
Mobile Sensors & Applications for Air Pollutants

Citizen Science Air Monitor (CSAM): Quality Assurance Guidelines

Evaluation of Field-deployed Low Cost PM Sensors

Air Sensor Guidebook

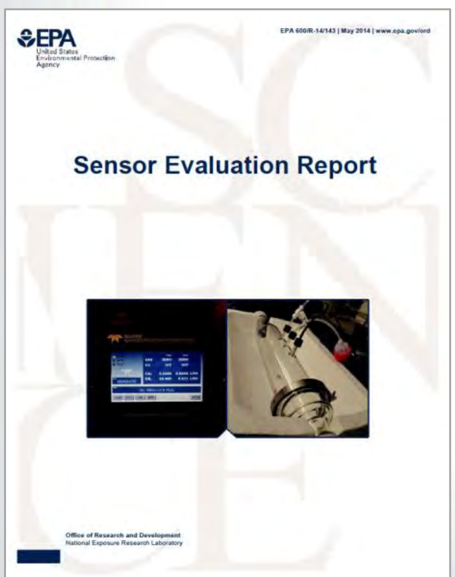
- A-to-Z resource for anyone interested in conducting an air monitoring project
- Topics include:
  - Air Quality 101
  - What to look for in a sensor
  - How to collect useful data
  - Sensor performance guidance
  - Maintaining your sensor
  - Potential questions from state and local officials
  - Technical considerations

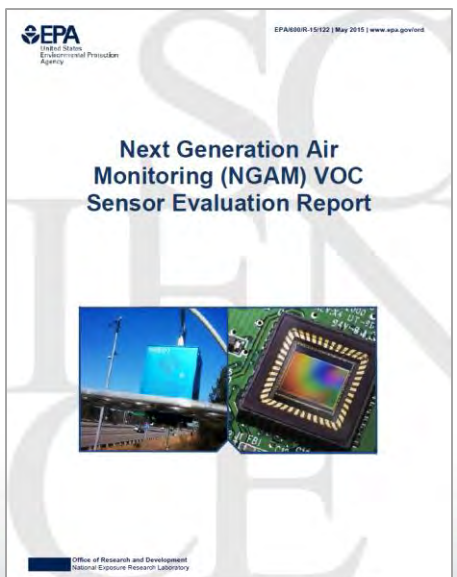


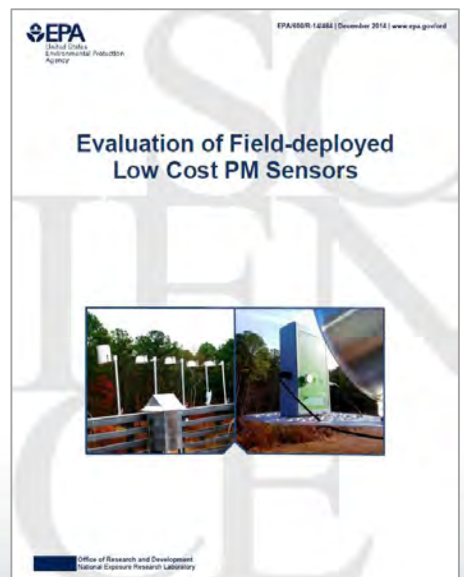
https://www.epa.gov/air-sensor-toolbox/how-use-air-sensors-air-sensor-guidebook

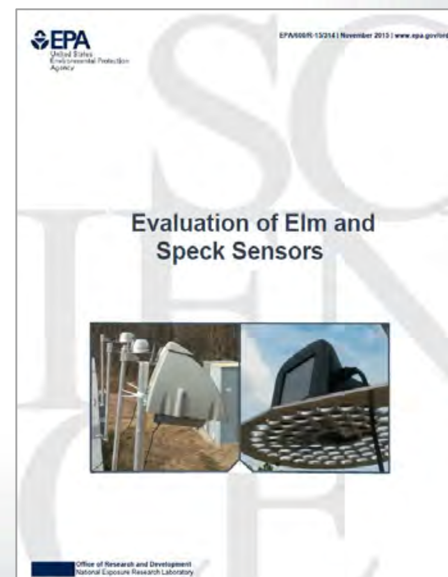
Example: Sensor Evaluation Reports

- Laboratory and field evaluations of select sensors on the market
- Evaluated performance characteristics:
    - R^2 (coefficient of determination) – sensor response compared to FEM/FRM
    - Effect of relative humidity and temperature on sensor response
    - Uptime
    - Ease of operation/installation
    - Mobility



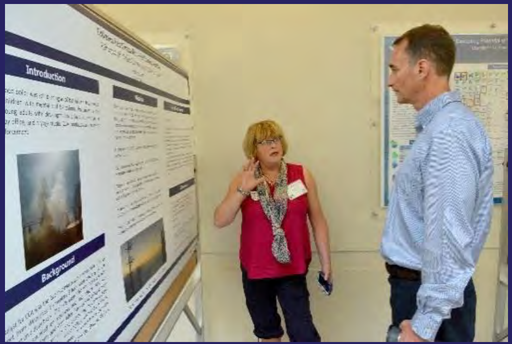






2015 Community Air Monitoring Training

- EPA hosted *A Glimpse into EPA's Air Sensor Toolbox on* July 9, 2015
    - o 30 community and tribal action group representatives participated in-person [800+ via webinar]
- Workshop Goals:
    - o To share tools, best practices, and resources from EPA's *Air Sensor Toolbox for Citizen Scientists*
    - o To educate interested groups and individuals on how to conduct successful air monitoring projects
- Follow-up
    - o Training has inspired participants to consider:
        - ▪ Appropriate redesigns of air monitoring projects, including alternative sensor choices
        - ▪ Recruiting air quality experts to assist with quality assurance/quality control
        - ▪ Establishing partnerships with local environmental experts to help with data interpretation (e.g., EPA Regional Offices; local universities)
    - o Workshop presentations are available on-line [http://www2.epa.gov/air-research/air-sensor-toolbox-citizen-scientists]



Popularity of Resources

Twitter metrics for #AirSensorMtg

176,735

Reaches

4,694,816

Impressions

Air Sensor Toolbox Webpage on EPA.gov

http://www2.epa.gov/air-research/next-generation-air-measuring-research

21340

~190 per week

Hits to Toolbox main page and resources since launch on June 1st, 2014

Training Video Series on YouTube

2137

Views since launched on Aug. 18th 2015

Sensor Application Challenges

1. Sensors have shown to be widely variable in performance value

2. Manufacturers not conducting basic testing

3. Lack of standard inhibits market growth and consumer/user confidence

4. Large multi-$B industry but most purchasers of technology (agencies or citizens) are not able to judge performance

5. Agency “gold standard” methods approval takes years and addresses only those appropriate for regulatory use

How Might EPA Advance Sensor Performance Knowledge?

1. Review steps others have previously taken (Energy Star, ASTM, UL)
2. FED/State/DoD discussions on pursuing a strategy
3. Have discussions with standards organizations (e.g., ANSI)
4. Develop extensive literature reviews (Clements et al.; Woodall et al.)
5. Determine the state of the science in sensor technology
6. Convene a workshop to hear independent POVs concerning basic performance
7. Summarize performance benchmarks having value in moving this effort forward

The Next Step on Sensor Performance: E-Enterprise Efforts

Exploring the development of an independent third-party sensor evaluation/certification program

- Develop sensor performance targets for $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3
- 2018 workshop (RTP, NC and web access) planned for June 25-26th)
  - Open meeting – webinar for all interested parties to provide individual input
  - Invited experts to provide individual input on suggested performance targets for $PM_{2.5}$ and O_3
- Post workshop final report or journal publication of targets and rationale
- Concurrently meeting with standards organizations
  - American National Standards Institute (ANSI) Meeting (November 1, 2017)
    - Convene members to facilitate discussion between EPA and private sector organizations to gauge their interest and processes for certification program development

Project Specific Findings

The Emerging Technologies research area includes more than the discovery/evaluation/application of low cost sensors. Project reports associated with some of the other research studies shall be further discussed:

- Michael Breen. The VTrac and Micro Trac-MP applications
- Brian Gullett and Amara Holder. Aerial platform and advancements in black carbon monitoring
- Jesse Bash. New gaseous ammonia monitoring technologies and modeling
- Jim Szykman. DISCOVER AQ and KORUS advanced technologies research projects
- Matt Landis and Kirk Baker. The Wildfire Sensor Challenge
- Paul A. Solomon. Mobile air quality sensor monitoring. The EPA/ACLIMA cooperative research agreements
- David Holland. Data Fusion Modeling
- Vasu Kilaru. Big Data and Data Analytics
- Richard Callan. Grant-based research investigating sensor use in community settings

State of Sensor Science

Ventilation Tracker (VTrac), Microenvironment Tracker for Mobile Phones (MicroTrac-MP), TracMyAir Mobile App

Michael Breen

Collaborators

- **NERL: Janet Burke, Peter Egeghy, Ronald Williams, Timothy Barzyk, Vasu Kilaru, David Lyons, Steven Prince**
- **NHEERL: Robert Devlin, David Diaz-Sanchez**
- **NCEA: Thomas Long, Jennifer Richmond-Bryant**
- **NCER: Vito Ilacqua**
- **OAR-OAQPS: John Langstaff, Stephen Graham**
- **OAR-ORIA: Laura Kolb**
- **NC State University: Christopher Frey**

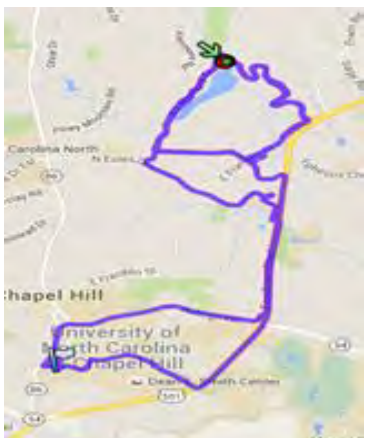
Overview

- Exposure Tracker (ETrac) model – predicts individual-level exposure metrics using wearable GPS loggers, accelerometers, and fine-scale outdoor concentrations
  - Ongoing
- Microenvironment Tracker for Mobile Phones (MicroTrac-MP) model – predicts time spent in various microenvironments based on geo-locations from mobile phones
  - MicroTrac-MP is an extension of MicroTrac model, which uses geo-locations from wearable GPS loggers
  - Ongoing
- Ventilation Tracker (VTrac) model – predicts ventilation rates based on wearable accelerometers and GPS loggers
  - Ventilation rates will be used to predict inhaled dose based on personal exposures
  - Ongoing
- Mobile App (TracMyAir) – predicts real-time exposure and dose metrics for PM2.5 and ozone using mobile phones
  - Ongoing

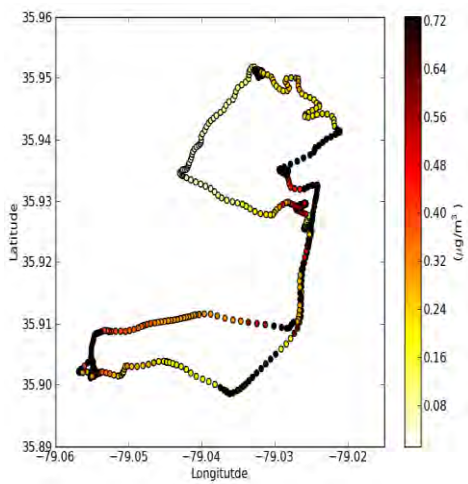
Results

- **ETrac model**
  - **Applied model for CADEE epidemiology study with GPS data from study participants to predict exposure metrics for PM2.5, NOx, EC, CO**
- **Developed Exposure Tracker (ETrac) model to predict fine-scale individual exposures**
  - **Outdoor air quality model (hourly, census block)**
    - **Kriging for background**
    - **R-line dispersion model for on-road emissions**
  - **House-specific dynamic infiltration model (continuous)**
  - **GPS-based time-location model (5 sec)**
    - **MicroTrac model for time spent in microenvironments**
- **Modeled exposures for ambient $PM_{2.5}$, NOx, CO, EC**
- **Predicted continuous exposures across 10 consecutive weeks for each individual**

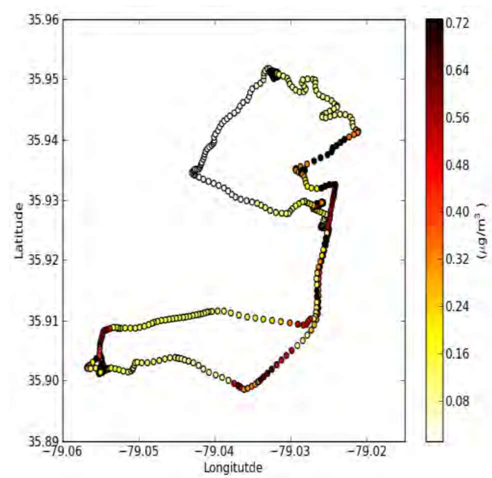
Exposure Tracker (ETrac)



GPS Map



PM$_{2.5}$ Outdoors (on-road)

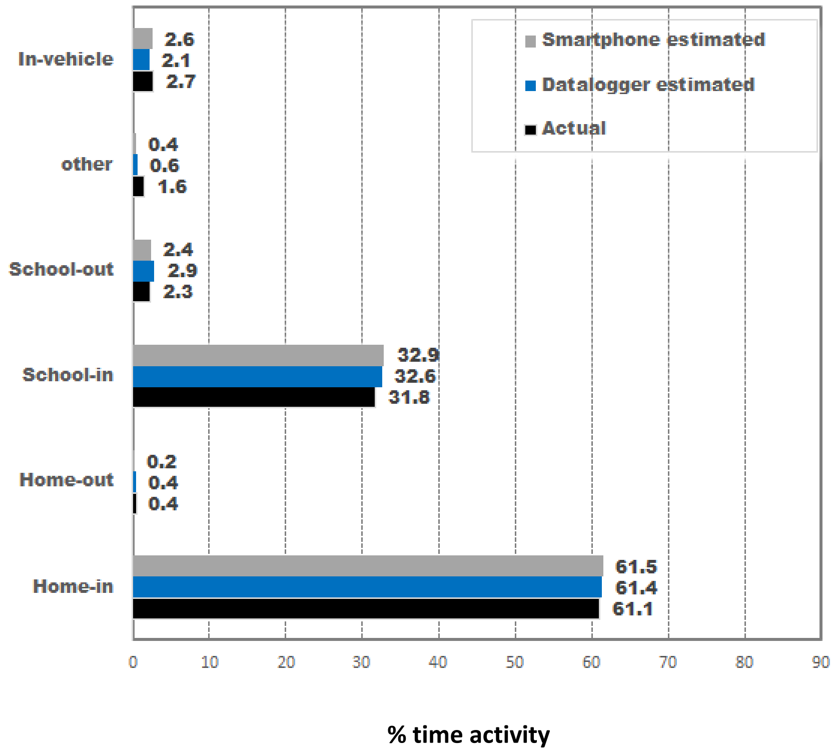


PM$_{2.5}$ Exposure (on-road)

Additional Results

- **MicroTrac-MP model**
  - **Evaluated model with diary data from pilot study**
  - **Preparing manuscript for peer-reviewed journal**
- **VTrac model**
  - **Applying model for CADEE (Coronary Artery Disease and Environmental Exposure) epidemiology study with accelerometer data from study participants**

MicroTrac-MP



- **MicroTrac-MP model was evaluated with smartphone location data**
- **Smartphone locations are determined from either GPS, cell towers, wifi locations, which can have different spatial accuracies**
- **MicroTrac-MP model showed high accuracy using data from smartphone**

Additional TracMyAir Efforts

- **TracMyAir mobile app**
  - **Preparing US Patent application**
  - **Developing mobile app for iPhone**

EPA

www.epa.gov/research

science in ACTION

INNOVATIVE RESEARCH FOR A SUSTAINABLE FUTURE

EPA's MyAir App: Using smart phones to predict near real-time air pollution exposures

Background

To better understand people's contact with air pollutants and their potential for adverse health effects, it's important to estimate how much time they spend in different locations and what the air pollutant concentrations are in those locations. Using currently available personal air monitors to collect this information has several limitations, including burden on participants, cost, and need for substantial technical expertise.

Alternatively, the currently available exposure models must be used by specially-trained researchers, and near real-time predictions are not possible since large and diverse input data (e.g., high temporally resolved air

The app uses input data available from iPhones, which includes:

- near real-time outdoor air

Microenvironment Tracker (MicroTrac), which account for time spent in different microenvironments – such as indoors and outdoors at home,

TracMyAir Mobile App

- Use smartphone to predict near real-time air pollution exposures (Patent pending)
  - Exposure model uses input data available from smartphones (e.g., local air monitor, local weather, user's location, user's home characteristics)
  - Accounts for attenuation of outdoor air pollution while indoors, and time spent in different microenvironments
  - Future integration with wearable health monitors to determine personal response to exposures

Applications of TracMyAir

- **Public health**
  - **Provides timely personalized notifications of exposure for susceptible individuals**
  - **Allows people to modify their behavior (e.g., go indoors, close windows, reduce activity level, operate home air cleaner)**
- **Epidemiology studies**
  - **Automated, real-time predictions of individual exposures**
  - **Facilitate use of modeled exposure metrics for epidemiology studies**

Benefits of TracMyAir Mobile App

- Real-time collection and processing of large, multidimensional model input data (nearest air monitor, outdoor temperature and wind speed, GPS, accelerometer)
- Allows for exposure forecasting by using air quality modeling forecasts and personalized time-activity histories
- Future integration with real-time air quality modeling (BigMap – T. Barzyk, V. Isakov)
- Future integration and deployment with SmokeSense App (NHEERL – A. Rappold) that collects health effects data during wild fires

EM-3 State of Sensor Science

Sensors for open area emission measurements

Brian Gullett
Amara Holder

Collaborators and Clients

- EPA
  - Bill Mitchell
  - Dale Greenwell
  - Ingrid George
- UDRI – Johanna Aurell, Trevor deCastro
- USGS – Todd Hoefen, Jon Stock, Bruce Quick
- USFS – Shawn Urbanski, Dan Jimenez
- Canadian Forestry Svc – Joshua Johnston
- NASA – Ved Chirayath

- Clients
  - OAQPS
  - Regions (R7)
  - DOI – BSEE
  - DoD
  - USCG

Open Area Emissions-Overview

- Objectives:
  - Develop an emission sampling system applicable to the high concentrations found in near-source, open-area plumes
  - Test commercially-available sensors for sensitivity, response, recovery under plume conditions
  - Combine commercial and EPA-built samplers with sensors into a versatile, lightweight system capable of aerial sampling
  - Field test systems, verify performance, and determine emission factors
  - Develop improved, real-time monitors (PM, black carbon)

Open Area Emissions-Overview

Field campaigns:

- –Prescribed burns, forests and grasslands
- –Demilitarization
- –Oil burns on water
- –Kerosene and natural gas burns
- –Open burns of waste
- –Air curtain incinerators
- –Compositional effects on emissions

Open Area Emissions-Overview

- Emission factor determination during open burning of propellant, McAlester Army Ammunition Plant, Oklahoma and Radford AAP, VA.
  - Determine emission factors for opening burning.
  - Internal report done, database under development.
- ARL
  - Develop methods for discerning emissions from gun firing and detonations
  - SERDP (Strategic Environmental Research and Development Program) report done, white paper in draft to continue work, writing underway.
- Prescribed burning at the Sycan Marsh, Oregon.
  - Determine emission factors for grassland burns.
- Prescribed burning at Tallgrass Prairie National Preserve and Konza Prairie Biological Station (both Kansas).
  - Determine emission factors for grassland burns; discern differences between spring and fall burns.
  - Preliminary field tests of NO, NOx sensors.
  - Field test of particle sensor and black carbon sensor.
  - Sampling done. Data analysis and writing underway.

Results

The Aerostat/Flyer

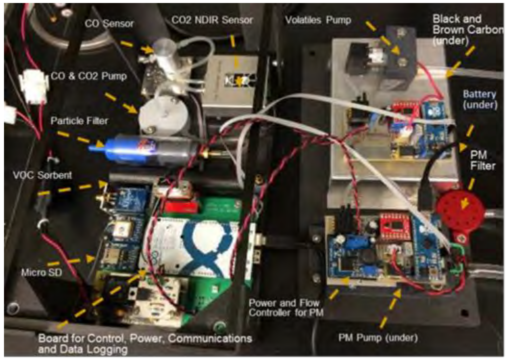
The Flyer

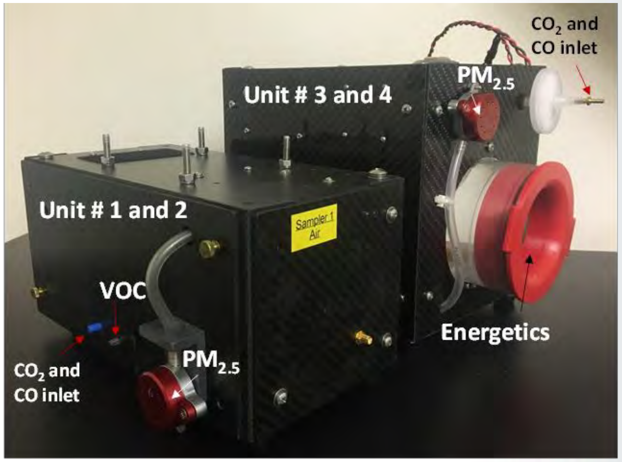
The “Flyer,” a 22 kg sensor/sampler instrumentation package, was designed and built to be lofted into plumes by a 5 m diameter, helium-filled aerostat. The aerostat is attached to one or two tether lines that are reeled onto winches and mounted on the back of 4WD utility vehicles.

Results (Cont'd)

NASA Hexacopter and Kolibri

Kolibri internals





Two versions of the Kolibri

The "Kolibri" is a smaller, lighter (<4.5 kg) sensor/sampler system designed for use with an unmanned aerial system (UAS), or drone.

Results (Cont'd)

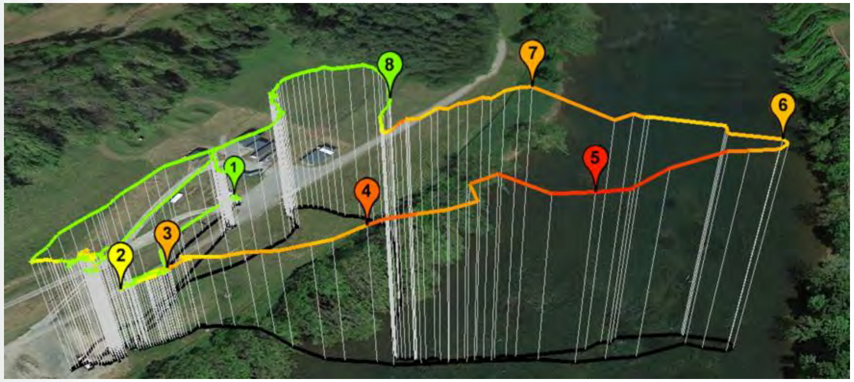
Measurement capabilities

Analyte	Emission Sampling Method	Instrument	Sub Task
CO_2	Flyer	LICOR-820	1,3-5
	Kolibri	DX62210/DX6220	6
CO	Flyer and Kolibri	e2V EC4-500-CO	1,3-6
$PM_{2.5}$ and PM_{10}	Flyer	47 mm Teflon filter	1,3-5
	Kolibri	37 mm Teflon filer	6
PM_{Total}	Kolibri	47 mm Teflon filter	6
PM distribution	Flyer	DustTrak DRX 8533	1,4
Elements	Flyer and Kolibri	XRF	3,6
HBr/HCl	Flyer	Alkali coated quartz filter	4
PCDDs/PCDFs	Flyer	Filter PUF/XAD/PUF sorbent tube	1,4
PBDDs/PBDFs	Flyer	Filter PUF/XAD-2/PUF sorbent tube	4
PAHs	Flyer	Filter PUF/XAD-2/PUF sorbent tube	1,3,4
VOCs	Flyer	SUMMA Canister	1,3-6
	Kolibri	CarboTrap 300	6
Carbonyls	Flyer	DNPH cartridge	1
Nitrocellulose	Kolibri	150 mm Quartz filter	6
	Flyer	47 mm Quartz filter	3
Nitroaromatics	Kolibri	150 mm Quartz filter	6
	Flyer	47 mm Quartz filter	3

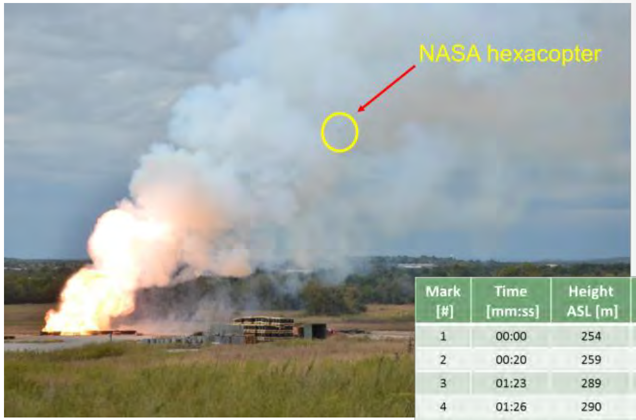
Results (Cont'd)

Radford AAP

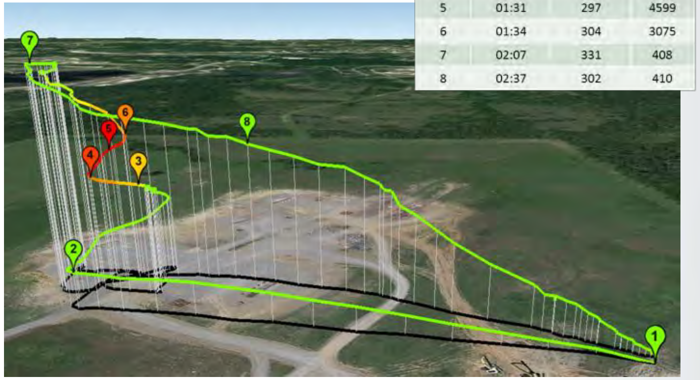
Mark [#]	Time [mm:ss]	Height ASL [m]	CO_2 [ppm]
1	00:00	524	431
2	00:49	542	1851
3	02:25	544	2831
4	02:39	561	3441
5	02:47	572	4085
6	02:54	583	2562
7	03:02	602	2678
8	07:13	586	436



McAlester AAP



Mark [#]	Time [mm:ss]	Height ASL [m]	CO_2 [ppm]
1	00:00	254	416
2	00:20	259	408
3	01:23	289	2427
4	01:26	290	3778
5	01:31	297	4599
6	01:34	304	3075
7	02:07	331	408
8	02:37	302	410



Results (Cont'd)

Kansas prescribed burns

Tallgrass Prairie

Konza Prairie

Next Steps – 3 years

- Validate NO, NOx sensors
- Finish PM(t) sensor
- Design, build, and test unmanned ground vehicle (UGV)
- Add HC, SO_2, CH_4 sensors
- Document the protocols and procedures
- Develop interchangeable sensor/sampler architecture

EM-3 State of Sensor Science

Black carbon sensor development and evaluation

Amara Holder

Collaborators

- Steven and Jeff Blair / Aethlabs
- Brian Gullett / ORD/NRMRL
- Sue Kimbrough / ORD/NRMRL
- Joann Rice / OAQPS

Black Carbon Sensor-Overview

The primary objective of this project was to develop a black carbon sensor that has a small form factor, low power requirements, and requires minimal maintenance

We partnered with Aethlabs to develop a black carbon sensor that met the measurement needs of EPA researchers

One prototype (MA350) was tailored to ambient monitoring with a weatherproof case, lower power requirement and minimal hands on maintenance requirements

A second prototype (MA200) was designed for near source aerial measurements with a minimized weight and size at the expense of shorter battery life and shorter maintenance free operation

Small size (7.9”x 4”x2.75”) weatherized case

Li-ion battery, low power draw ~5W

5 measurement wavelengths: 880, 625, 528, 470, 375 nm

Long life 84 spot filter cartridge

Black Carbon Sensor Overview (Cont'd)

The prototype instruments were tested in a variety of environments at both high and low particulate matter concentrations

2 ambient monitoring campaigns:

- **May – July 2016 at the Triple Oak Raleigh near-road site**
- **January – May 2017 at the Ambient Air Innovative Research Site (AIRS) in RTP**

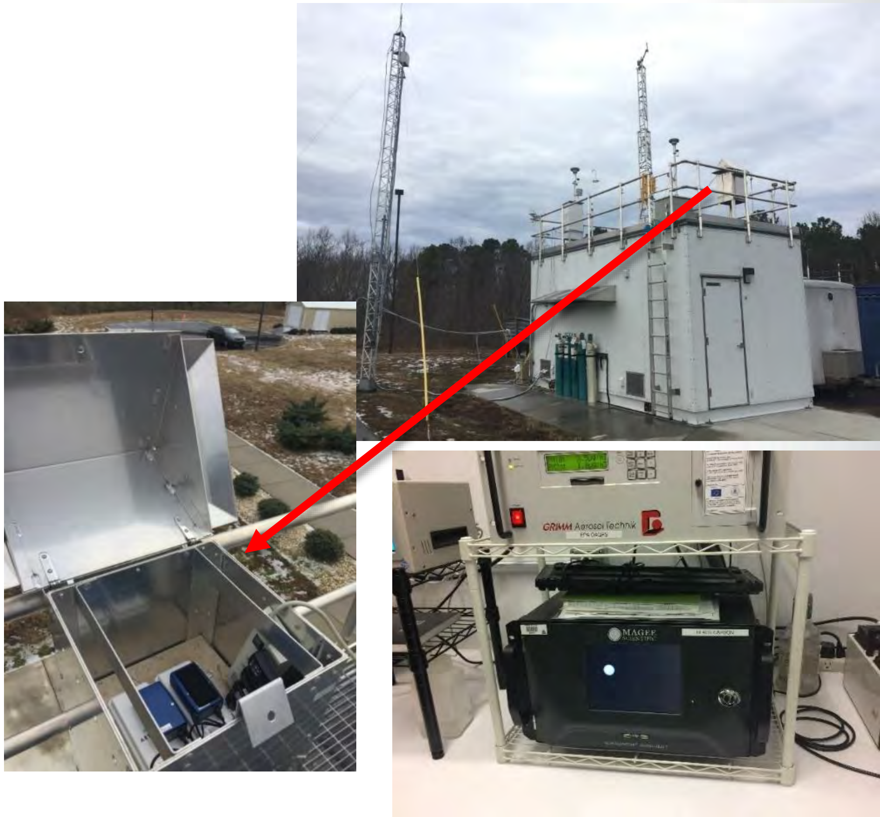
Encountered a variety ambient conditions
Temperature 5 to 33 °C, RH 16 to 100%

2 source measurement campaigns:

- **Kerosene pool fire & propane burner**
- **Grassland prescribed fire**

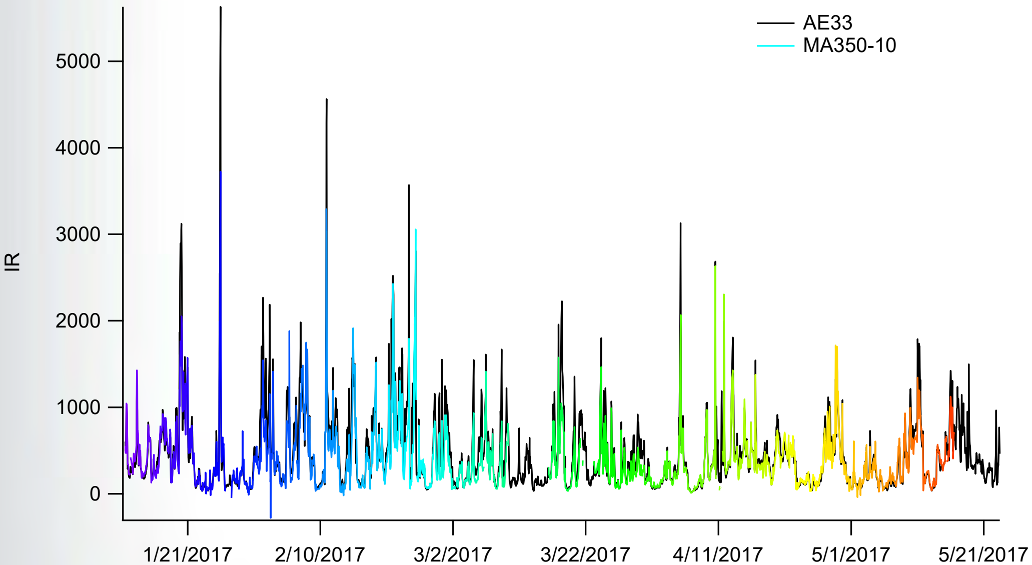
Encountered a range of concentrations (0 to 3 µg/m³) and particulate
matter with varying optical properties (e.g., white, brown, black smoke)

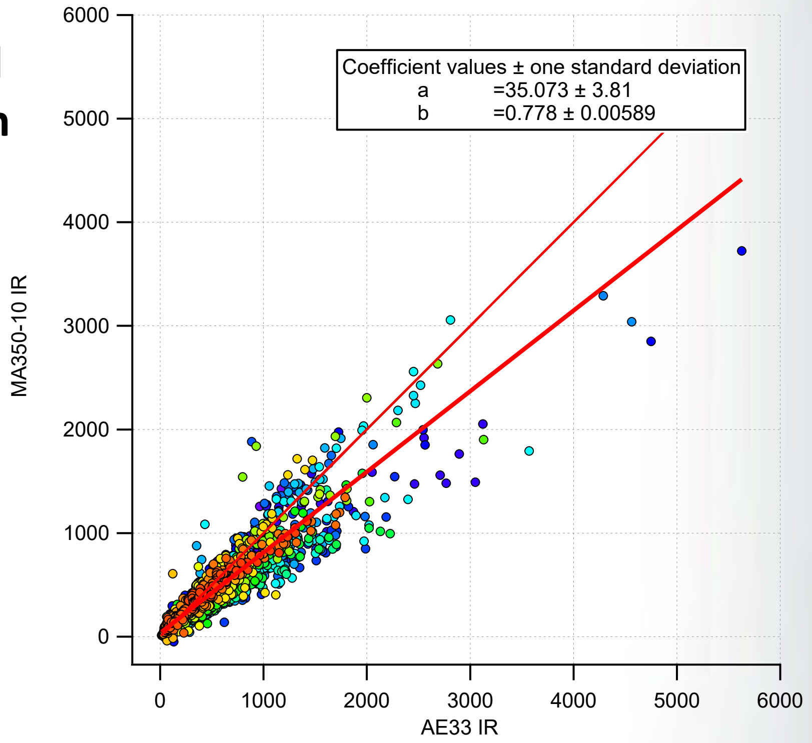
Compared to reference instruments:
AE33 – Seven wavelength Aethalometer
AE22 – Dual wavelength Aethalometer
AE51 – Microaethalometer



Results

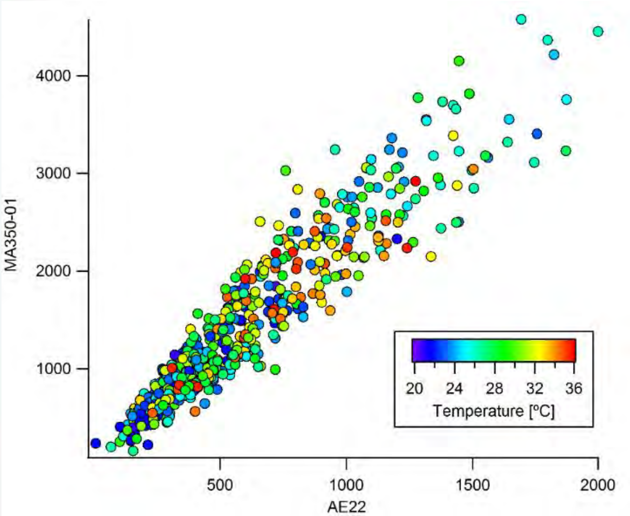
BC sensor is highly correlated with reference instrument (AE33) (r^2>0.85), however the measured concentrations are somewhat lower (73 – 85%) than the reference measurement

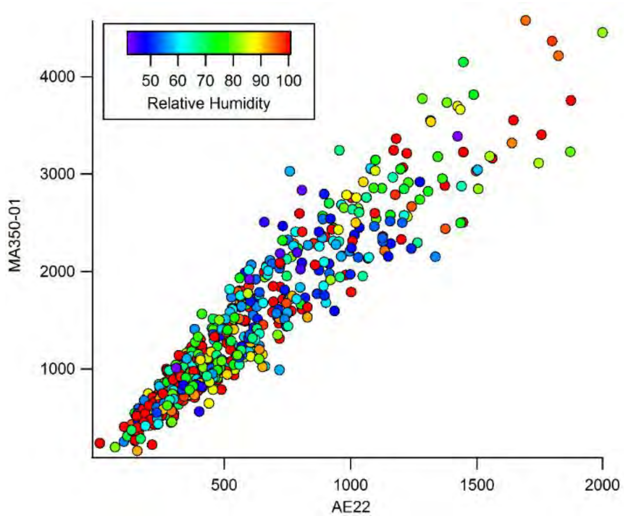




Results

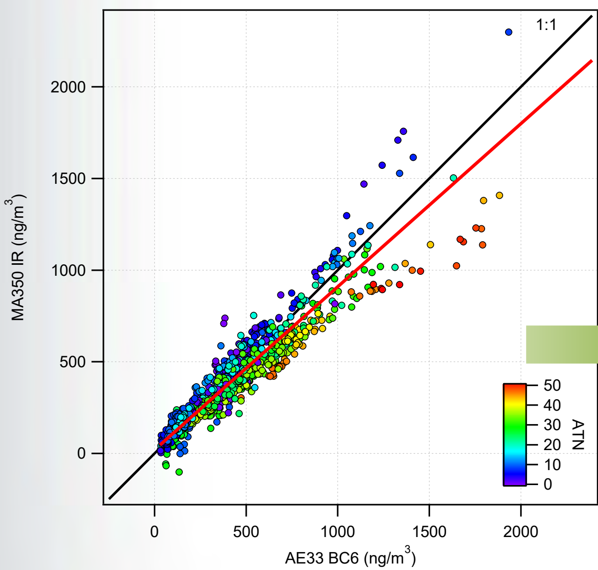
Unlike previous versions of the Aethalometer there was minimal evidence of an impact from relative humidity or temperature on the correlation between the black carbon sensor and the reference instruments



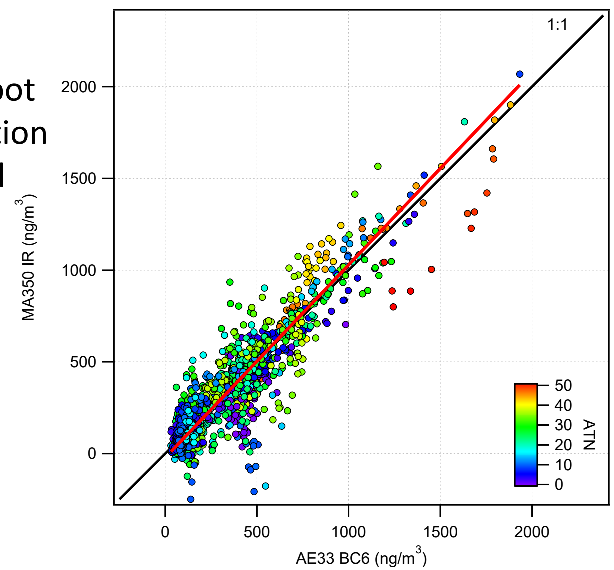


Results

Black carbon sensor exhibits a filter loading artifact where the black carbon concentration is artificially reduced at higher attenuation (ATN) values. Dual spot correction improves the correlation between the instruments, but also increases the noise of the measurement



Dual spot correction applied



Dual spot correction is even more important for accurately measuring source level black carbon concentrations

Burn	BC sensor/BC reference	Dual Spot Corrected BC sensor/BC reference
Propane #2	0.65	0.81
Propane #3	0.37	0.79

Next Steps

- **Continue analysis of existing datasets**
  - **Analyze source measurements**
  - **Refine dual spot methodology for loading artifact correction**
- **Continue source measurements with black carbon reference materials to refine calibration coefficients for multiple measurement wavelengths**
- **Prepare manuscript to summarize the comparability of the black carbon sensor with existing measurement technologies**

Evaluation and development of NH_3 emissions for air-quality modeling platforms

Jesse Bash

Introduction

- Advance Applications and Integrated Monitoring for Air Quality
  - Task leads: James Szykman and Jesse Bash
- Combined measurements and modeling to evaluate and constrain modeled processes
  - Used network observations, high resolution observations, and satellite imagery
  - Allowed for the rapid development of NH_3 emission and deposition updates
- Supports Nitrogen Roadmap, OAQPS, and the Chesapeake Bay Program
- Highly leveraged outside the agency
  - Work has been externally supported by NASA, USDA, and the European Union's Research and Innovation FP7

University of Colorado Boulder
Environment and Climate Change Canada / Environnement et Changement climatique Canada
aer
JPL Jet Propulsion Laboratory California Institute of Technology
RICE
Centre for Ecology & Hydrology NATURAL ENVIRONMENT RESEARCH COUNCIL
HARVARD UNIVERSITY
INRA SCIENCE & IMPACT

Motivation

- Nitrogen (N) is an essential nutrient for all life
- A single molecule of reactive N, created through natural or man-made processes, can cycle through various environmental systems—the atmosphere, terrestrial ecosystem, and aquatic ecosystems—where it can be transformed or temporarily stored
  - Reactive N, which is naturally produced via enzymatic reactions, forest fires and lightning and anthopogenically produced vial fossil fuel combustion and synthesis of fertilizers
  - The anthropogenic contribution to this cycle is now larger than natural sources in the United States and globally
- Atmospheric reactive N is largely composed of Ammonia (NH_3) and Nitrogen Oxides (NO_x)
  - $NH_3$is the most abundant atmospheric base and emissions remain largely controlled via voluntary measures
- NH_3 is an ambient aerosols precursor and is a significant component (~50%) of reactive N deposition
  - Contributes to biodiversity loss, soil acidification, surface water eutrophication, and harmful algal blooms
  - Contributes to adverse respiratory and cardiac responses

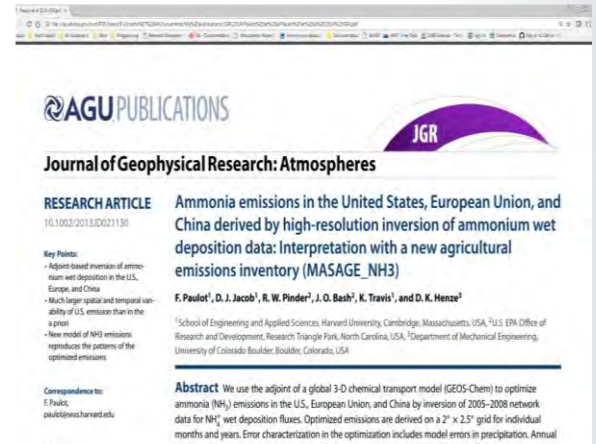
Publications

10 publications

- Rasool et al., *Geosci. Model Dev.*, 2016
- Hogrefe, C. (ed.), EM, 2015
- Bash et al., *EM, 2015*
- Shephard et al., *Atmos. Meas. Tech., 2015*
- Zhu et al., *Atmos. Chem. Phys.*, 2015
- Zhu et al., *Current Pollution Reports*, 2015
- Luo et al., *Atmos. Environ., 2015*
- Paulot et al., *J. Geophys. Res.-Atmos.*, 2014

Paulot et al., 2014

- U.S., E.U., and China top down NH_3 emissions estimates
  - Used U.S., E.U. and Asian wet deposition measurements to optimize emissions
- Developed a simple process based model of bottom up NH_3 emissions to interpret the top down emissions optimization
  - Used the mechanistic model to estimate crop and animal emissions
- Mechanistic model was used to interpret potential sources/mechanisms of NH_3 emissions
  - Useful to identify methods for emission reductions


AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2013JD021130

Key Points:
- Adjoint-based inversion of ammonium wet deposition in the U.S., Europe, and China
- Much larger spatial and temporal variability of U.S. emission than in the a priori
- New model of NH3 emissions reproduces the patterns of the optimized emissions

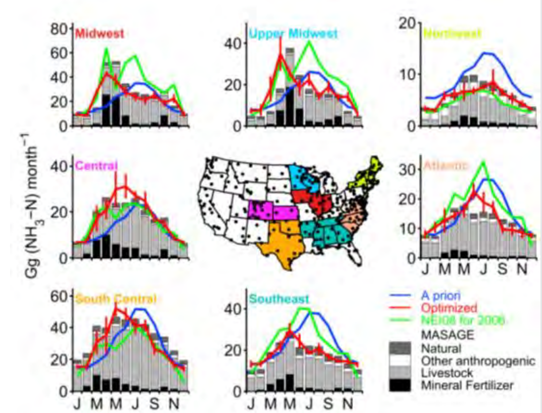
Correspondence to:
F. Paulot,
paulot@seas.harvard.edu

Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: Interpretation with a new agricultural emissions inventory (MASAGE_NH3)

F. Paulot[1], D. J. Jacob[1], R. W. Pinder[2], J. O. Bash[2], K. Travis[1], and D. K. Henze[3]

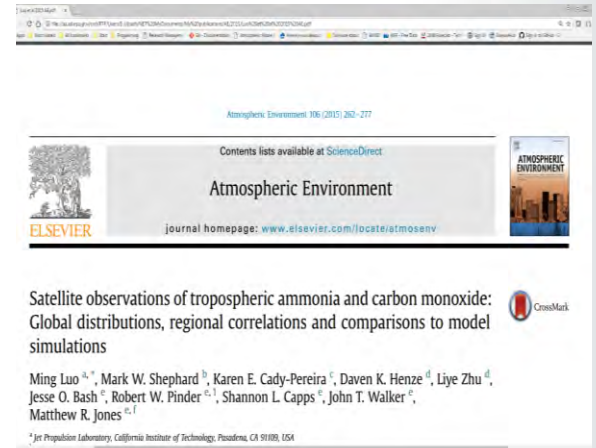
[1]School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, USA, [2]U.S. EPA Office of Research and Development, Research Triangle Park, North Carolina, USA, [3]Department of Mechanical Engineering, University of Colorado Boulder, Boulder, Colorado, USA

Abstract We use the adjoint of a global 3-D chemical transport model (GEOS-Chem) to optimize ammonia (NH_3) emissions in the U.S., European Union, and China by inversion of 2005–2008 network data for NH_4^+ wet deposition fluxes. Optimized emissions are derived on a 2° × 2.5° grid for individual months and years. Error characterization in the optimization includes model errors in precipitation. Annual



Lou et al., 2015

- Estimated NH_3:CO ratios from the TES (Tropospheric Emissions Spectrometer) instrument on the Aura satellite
  - Compared well with observations
  - Used to identify seasonal global biomass burning and atmospheric CO and NH_3 enhancements
  - Could not differentiate biomass burning where large urban influences were present
- Useful in constraining biomass NH_3 emissions in inventories where CO emissions are better quantified


Atmospheric Environment 106 (2015) 262–277

Contents lists available at ScienceDirect

Atmospheric Environment

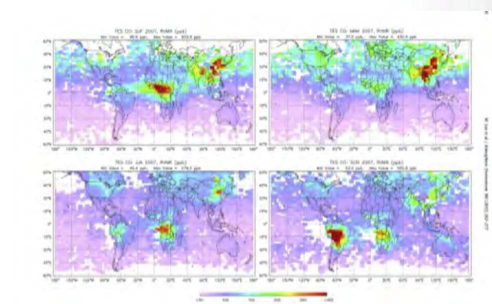
journal homepage: www.elsevier.com/locate/atmosenv

ELSEVIER

Satellite observations of tropospheric ammonia and carbon monoxide: Global distributions, regional correlations and comparisons to model simulations

Ming Luo[a,*], Mark W. Shephard[b], Karen E. Cady-Pereira[c], Daven K. Henze[d], Liye Zhu[d], Jesse O. Bash[e], Robert W. Pinder[e,1], Shannon L. Capps[e], John T. Walker[e], Matthew R. Jones[e,f]

[a] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA



Zhu et al., 2015

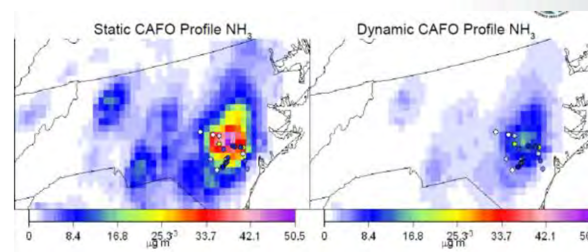
- Ammonia can be either emitted or deposited depending on environmental conditions (bidirectional NH_3 exchange)
  - Impacts NH_3 atmospheric lifetime and fate
- Evaluation of bidirectional NH_3 exchange and new diurnal NH_3 animal emissions parameterization in GEOS-Chem
  - Bidirectional NH_3 exchange was in GEOS-Chem was developed following the CMAQ application
  - Diurnal animal NH_3 emissions were developed fowling the temperature dependence discussed in Sutton et al., 2013
- Improved model performance
  - Bidirectional exchange increased summer and reduced spring NH_3 ambient
  - Diurnal animal NH_3 emissions reduced global NO_3 aerosol concentrations and improved ambient NH_3 estimates where we had hourly data
  - Large ambient NH_3 biases still exist

Atmos. Chem. Phys., 15, 12823–12843, 2015
www.atmos-chem-phys.net/15/12823/2015/
doi:10.5194/acp-15-12823-2015

Atmospheric Chemistry and Physics
EGU

Global evaluation of ammonia bidirectional exchange and livestock diurnal variation schemes

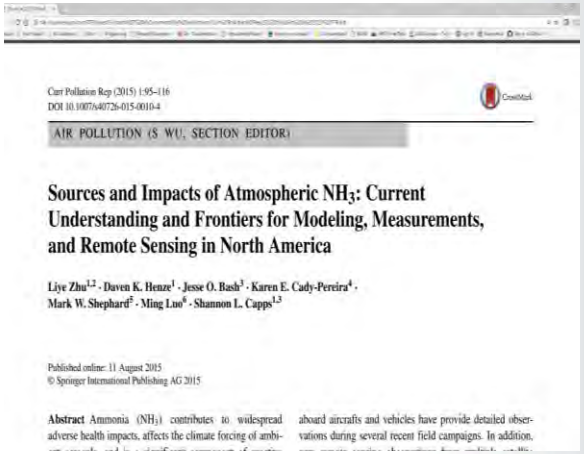
L. Zhu[1], D. Henze[1], J. Bash[2], G.-R. Jeong[1,2], K. Cady-Pereira[3], M. Shephard[4], M. Luo[5], F. Paulot[6,7], and S. Capps[2]
[1]Department of Mechanical Engineering, University of Colorado, Boulder, Colorado, USA
[2]US Environmental Protection Agency, Research Triangle Park, North Carolina, USA
[3]Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA
[4]Environment Canada, Toronto, Ontario, Canada
[5]Jet Propulsion Laboratory, California Institute of Technology Pasadena, CA, USA
[6]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey, USA
[7]Geophysical Fluid Dynamics Laboratory/National Oceanic and Atmospheric Administration, Princeton, New Jersey, USA



	Mean	NMB
Observations	7.5 $\mu g\ m^{-3}$	-
NEI Profile	25 $\mu g\ m^{-3}$	238%
New Profile	8.1 $\mu g\ m^{-3}$	9%

Zhu et al., 2015

- Review of NH_3 emissions and atmospheric NH_3 in North America
  - Summarizes the work of previous publications
  - Identifies modeling and measurements needs for North America
- Modeling needs to better address the bidirectional nature and the seasonal and diurnal emissions of NH_3
- Measurements are still limited in spatial and temporal coverage for North America and the World
  - Potential geostationary satellite with high resolution near-infrared spectrometer would help reduce the measurement deficit


Curr Pollution Rep (2015) 1:95–116
DOI 10.1007/s40726-015-0010-4

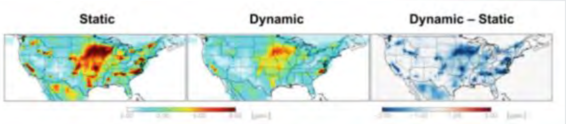
AIR POLLUTION (S WU, SECTION EDITOR)

Sources and Impacts of Atmospheric NH_3: Current Understanding and Frontiers for Modeling, Measurements, and Remote Sensing in North America

Liye Zhu[1,2] · Daven K. Henze[1] · Jesse O. Bash[3] · Karen E. Cady-Pereira[4] · Mark W. Shephard[5] · Ming Luo[6] · Shannon L. Capps[1,3]

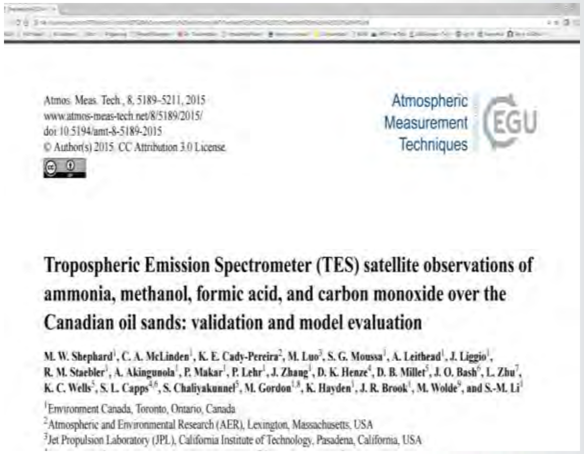
Published online: 11 August 2015
© Springer International Publishing AG 2015

Abstract Ammonia (NH_3) contributes to widespread adverse health impacts, affects the climate forcing of ambi- … aboard aircrafts and vehicles have provide detailed observations during several recent field campaigns. In addition,



Shephard et al., 2015

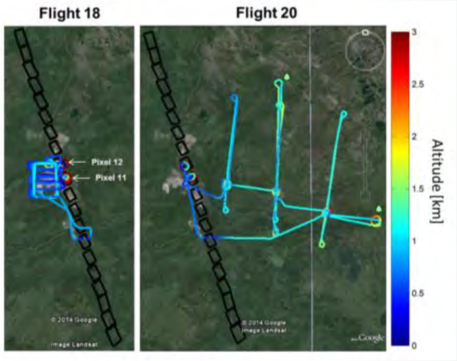
- TES satellite retrievals of ammonia, methanol, formic acid and carbon monoxide observations at the Canadian oil sands
- Evaluation of Environment Canada's Global Environmental Multi-scale – Modelling Air quality and CHemistry (GEM-MACH) modeling system
- Aircraft observations used to evaluate both TES observations and GEM-MACH estimates
- Ammonia and CO were elevated above the oil sands
  - TES and aircraft observations were similar
  - GEM-MACH underestimated ambient NH_3
    - Investigating bidirectional NH_3 exchange


Atmos. Meas. Tech., 8, 5189–5211, 2015
www.atmos-meas-tech.net/8/5189/2015/
doi:10.5194/amt-8-5189-2015

Atmospheric Measurement Techniques
EGU

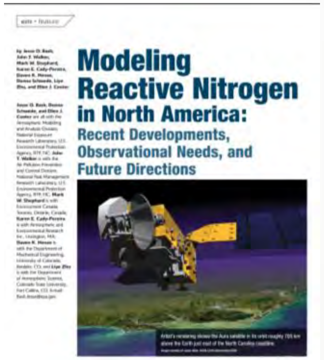
Tropospheric Emission Spectrometer (TES) satellite observations of ammonia, methanol, formic acid, and carbon monoxide over the Canadian oil sands: validation and model evaluation

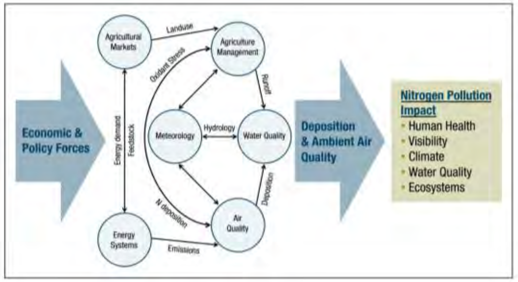
M. W. Shephard[1], C. A. McLinden[1], K. E. Cady-Pereira[2], M. Luo[3], S. G. Moussa[1], A. Leithead[1], J. Liggio[1], R. M. Staebler[1], A. Akingunola[1], P. Makar[1], P. Lehr[1], J. Zhang[1], D. K. Henze[4], D. B. Millet[5], J. O. Bash[6], L. Zhu[7], K. C. Wells[5], S. L. Capps[4,6], S. Chaliyakunnel[5], M. Gordon[1,8], K. Hayden[1], J. R. Brook[1], M. Wolde[9], and S.-M. Li[1]
[1]Environment Canada, Toronto, Ontario, Canada
[2]Atmospheric and Environmental Research (AER), Lexington, Massachusetts, USA
[3]Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, California, USA



Bash et al., 2015 EM

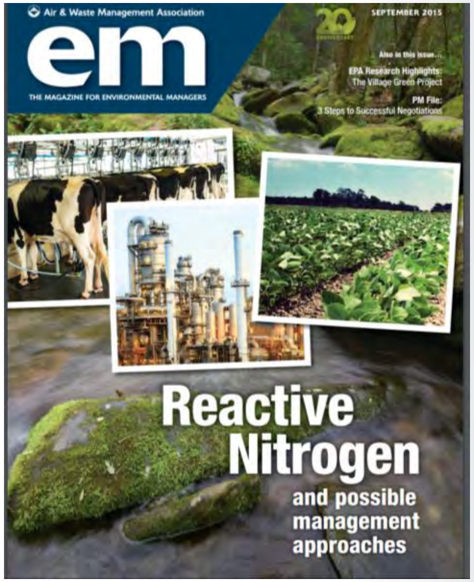
- Covered the nitrogen cycle/cascade and recent advancements in modeling it (in layman terms)
- Presents nitrogen management using a systems approach
  - Connection between N, energy and food and air and water quality are discussed
  - Connection of economic, air quality, water quality, and ecosystem and human health models discussed
- Presents the need to for multimedia observations to support evaluation of models, elucidate ecosystem response and effectiveness of controls of nitrogen pollution





EM Reactive Nitrogen Special Issue

- Special issue coordinated by CED (Computational Exposure Division) to examine air, water, ecosystem, and health aspects of nitrogen pollution from a North American and European perspective
- Contributions from:
  - University of Virginia
  - USDA ARS (Agricultural Research Service)
  - International Institute for Applied Systems Analysis (IIASA)
  - USDA Forest Service
  - Vrije Universiteit Amsterdam
  - EPA
- Authors provided a holistic systems analysis, discussion of controls in Europe and modeling and measurement needs



Rasool et al. 2016

- Developed a more complete soil NO emission model in CMAQ
- Connected it to the Environmental Policy Integrated Climate (EPIC) model
  - Crop growth and yield and nutrient management
- Regional evaluation using surface observations and NASA's Ozone Monitoring Instrument (OMI) satellite based NO retrieval
- Connection with EPIC now allows for the assessment of air quality changes ($PM_{2.5}$ and O_3) with agricultural management
- More complete parameterization of nitrogen cycling

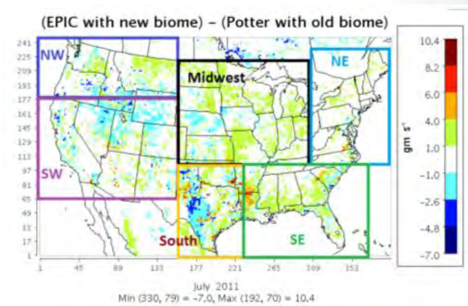

Geosci. Model Dev., 9, 3177–3197, 2016
www.geosci-model-dev.net/9/3177/2016/
doi:10.5194/gmd-9-3177-2016

Geoscientific Model Development
EGU

Enhanced representation of soil NO emissions in the Community Multiscale Air Quality (CMAQ) model version 5.0.2

Quazi Z. Rasool[1], Rui Zhang[1], Benjamin Lash[1,a], Daniel S. Cohan[1], Ellen J. Cooter[2], Jesse O. Bash[2], and Lok N. Lamsal[3,4]

[1]Department of Civil and Environmental Engineering, Rice University, Houston, TX, USA
[2]Computational Exposure Division, National Exposure Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Research Triangle Park, NC, USA
[3]Goddard Earth Sciences Technology and Research, Universities Space Research Association, Columbia, MD 21046, USA
[4]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[a]now at: School of Natural Sciences, University of California, Merced, CA, USA



Research Impact

- Contributed to the evaluation of the TES NH_3 retrieval
  - A NASA level 3 product from the Aura satellite
- Improved NH_3 emissions in CMAQ
  - As evaluated in the publications
- 2014 NEI is using CMAQ with bidirectional exchange estimated NH_3 emissions from fertilizer
  - Now includes activity data and fertilizer application rates from EPIC and emissions
- New diurnal animal production NH_3 profile incorporated into the NEI's emission processing platform and GEOS-Chem emissions processing platform
  - Now widely used in regional and global model simulations
- Bidirectional NH_3 exchange has been incorporated into GEOS-Chem

Summary and Next Step

- Existing collaboration have been extremely productive
- CMAQ's parameterization of nitrogen cycling has been expanded and evaluated
  - Developing a process level modeling system for nitrogen pollution
  - Ambient NH_3 biases still need to be addressed
- Collaborations
  - Rice University
    - Expanding soil N biogeochemistry
  - University of Maryland
    - Development of consistent NH_3 retrieval algorithms for AIRS, TES, CrIS satellite to extend available NH_3 observations in time and space
  - USDA ARS
    - In situ measurements of NH_3 emissions, transport and fate from animal production facilities
  - Universite Libre de Bruxelles
    - European Space Agency proposal for a satellite capable of high resolution reactive nitrogen (NH_3 and NO_x) observations

Advance Applications and Integrated Monitoring for Air Quality (A^2IM-AQ)

Jim Szykman, Lukas Valin, and David Williams
(In collaboration with Russell Long, Rachelle Duvall, and Andrew Whitehill)

Overarching Research Goals

Issue:

- Satellite Remote sensing of NO2, HCHO, SO2, O3, and AOD (PM) is rapidly advancing into high spatial and temporal resolution measurements much more relevant to air quality assessment and prediction –NOAA (VIIRS and GOES-R ABI) ESA (TROMPOMI) NASA (TEMPO and MAIA).
- Measurement incongruities currently prevent the ability for Air Quality Agencies to maximize the use of satellite data for air quality applications.

Approach:

- Conduct measurement research focused on improved harmonization of existing air quality monitoring networks and satellite measurements for improved quantitative use of satellite data, better characterization uncertainty and meaning at local air quality site.
- Through field campaigns (DISCOVER-AQ, KORUS-AQ, UWFPS, LMOS2017, etc.) characterize new near-commercial optical and remote sensing measurement methods (CAPS, QCL, lidar (ceilometers), ground solar spectrometers (pandora) to bridge the measurement incongruities for use in an integrated network design.
- Integrate research with more traditional NAAQS measurement research (Federal Reference Methods/Federal Equivalent Methods and Photochemical Assessment Monitoring Stations) under EM 1.6 to meet national and state needs.
- Develop a prototype integrated air quality monitoring station focused on key measurements to better connect column (satellite) to surface (in-situ) for NAAQS relevant observations.

EPA

ACE Emission and Measurements 3 – Changing the Paradigm of Air Pollution Monitoring:

Task 3.3 Advance Applications and Integrated Monitoring for Air Quality (A2IM-AQ)

EPA/NASA/NOAA Integrated System: 100's of millions of hourly measurements in near real time.

Leveraging Traditional FRM/FEM Research under Task 1.6 along with National Assets and Resources of Partners to conduct field campaigns/research in Countries Worst pollution Cities with outputs relevant to NAAQS monitoring

Federal Partners: NASA, NOAA

State and regional Partners:
CDPHE, MDE, CARB, TCEQ, WI DNR, LADCO, UDEQ, NESCAUM, MARAMA

International Partners:
NIER, ESA, KNMI

TEMPO

TROPOMI

$LISO_3$ Study

LMOS2017

UWFPS 2017

KORUS-AQ

DISCOVER-AQ

Advancing Measure Science for Regulatory Use

GOES-16 and TEMPO (cira 2020)
- Integration of new measurement technology into existing EPA networks – FRM/FEM, ceilometers, ground-based spectrometers

-Characterize column diurnal profiles of key pollutants to inform and improve emission on NO2/NOx and HCHO monitoring for NAAQS
Develop new satellite-based AQ products

LISO3 Study and TROPOMI
- FRM/FEM - Ozone and NO2
- Remote Sensing - NO2 & HCHO columns and mixing heights

-Establish integrated measurements sites using existing PAMS/NCore Network infrastructure under PAMS-EMP to provide improved monitoring for NAAQS

UWFPS and LMOS
- FRM/FEM - Ozone and NO2
- Remote Sensing - NO2 & HCHO columns and mixing heights

-Support for PAMS new mixing height requirement in extreme conditions.
-Assessment of high resolution surface/column NO2 with mixing heights below 300-500m

KORUS-AQ South Korea
- FRM/FEM - Ozone and NO2
- Remote Sensing - CH2O and NO2 columns, mixing heights
- Ozonesondes, Small sensors, Outreach

--First field evaluation of panodra column density CH2O within combined in-situ surface (EPA) and aircraft (NASA)
-Continued assessment of measurements for PAMS new mixing height requirement in high aerosol environment

DISCOVER-AQ/FRAPPE Denver:
- FRM/FEM - Ozone and NO2
- Compact Instruments/Sensor - Citizen Science
- Remote Sensing – Mix height and NO2 columns

-Assessment of ceilometer mixing heights for PAMS
-Successful Citizen Science Application for sensor evaluation, and assessment of pollutant variability.
-Integrated analysis connecting surface and column measurements for emissions and model evaluation

Traditional NAAQS FRM/FEM **100's** of hourly measurements in CONUS

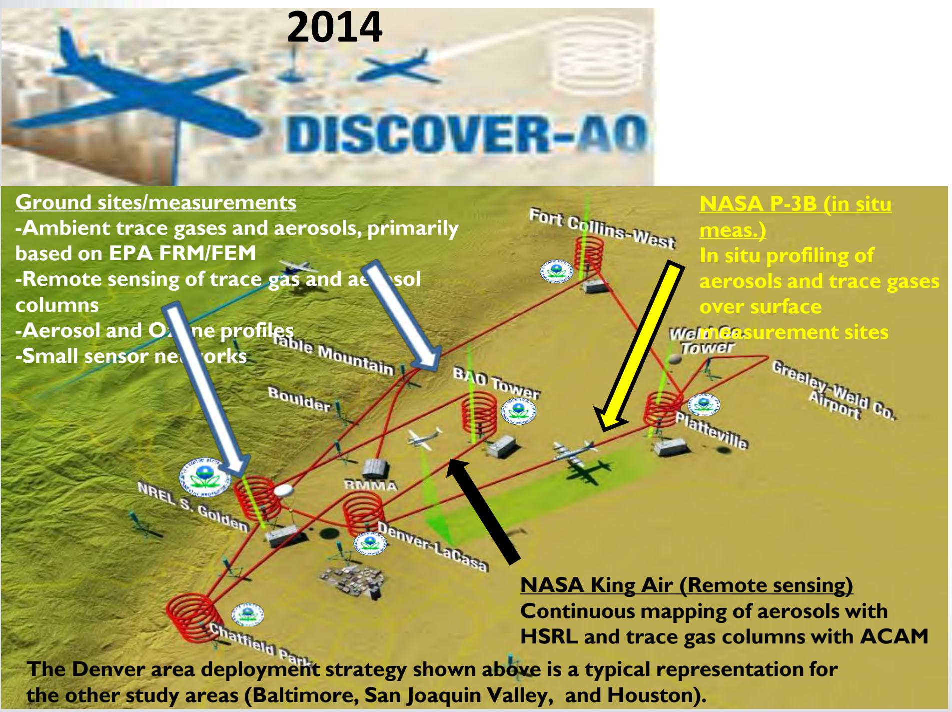
Current trajectory:
Steady evaluation of advanced measurement technology relevant to gaps in NAAQS regulatory monitoring.

- Integrated observing system
- IT infrastructure to distribute data in near real time
- Enhanced relationships with state partners

2014 2015 2016 2017 2018 2019 2020

Outputs/Products include timely archival/publication of all EPA research data

- **EPA data** collected under each field campaign **finalized and published** in a public archive **within 9 months of completed field activities**.
- Data made available to broader research community enhances utility of EPA data while NERL researchers continue R&A activities towards outputs and products, including publications.

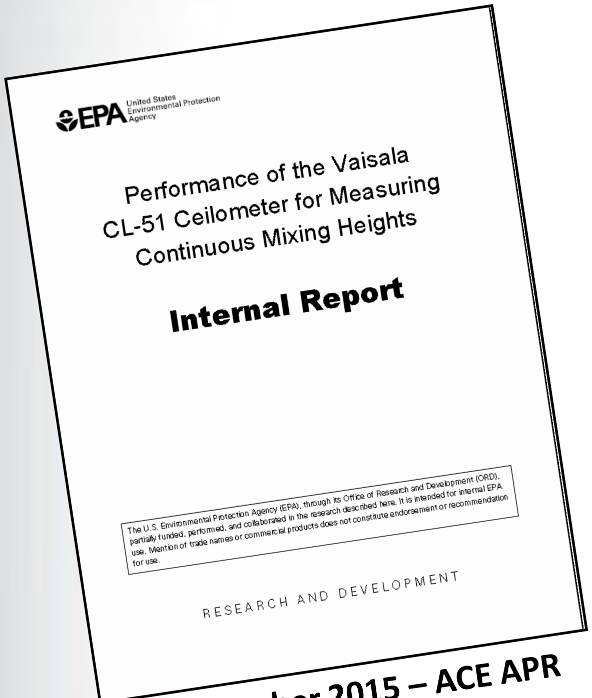


2016 KORUS-AQ

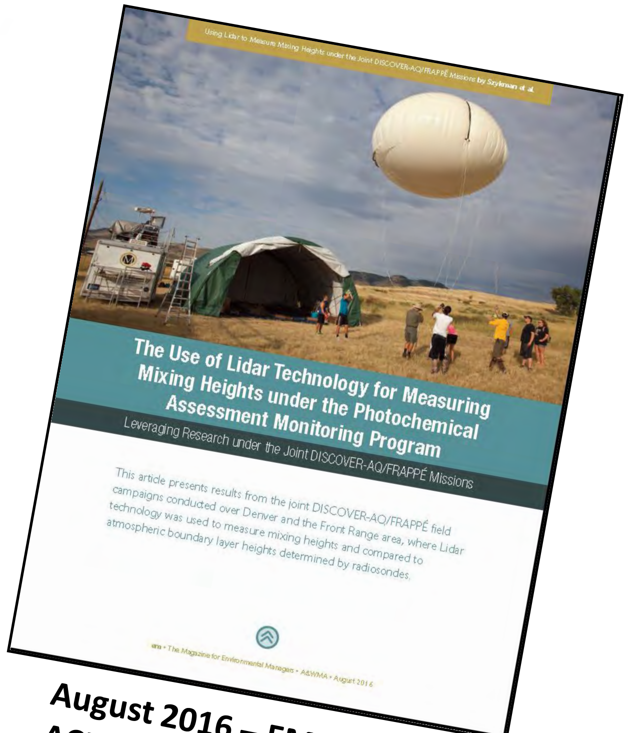
2017 UTAH WINTER FINE PARTICULATE STUDY — UWFPS 2017

Lake Michigan Ozone Study 2017

Outputs/Products (2014-2017): In Field Assessment of ceilometers for measuring Mixing Height directly supported new PAMS measurement requirement



September 2015 – ACE APR



August 2016 – EM Magazine ACE Product

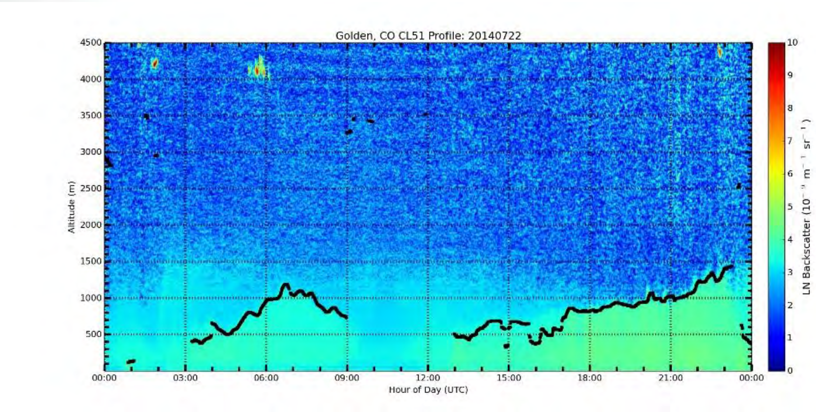
October 2017 –Atmos. Meas. Tech.

Kevin A. Cavender, OAQPS, PAMS National Program Manager – "This work was both timely and valuable to OAQPS and its State partners. …completion of this work will allow EPA to confidently recommend low cost ceilometers as an option for states needing to make this measurement…the evaluation of the open source algorithm (STRAT) may allow us to move to a centralized data collection and review system that will greatly reduce burned on the States while improving data validation and comparability across the network."

An Integrated Approach: Performance Evaluation of ceilometers for PAMS Mixing Level Height Requirement in differing Environments

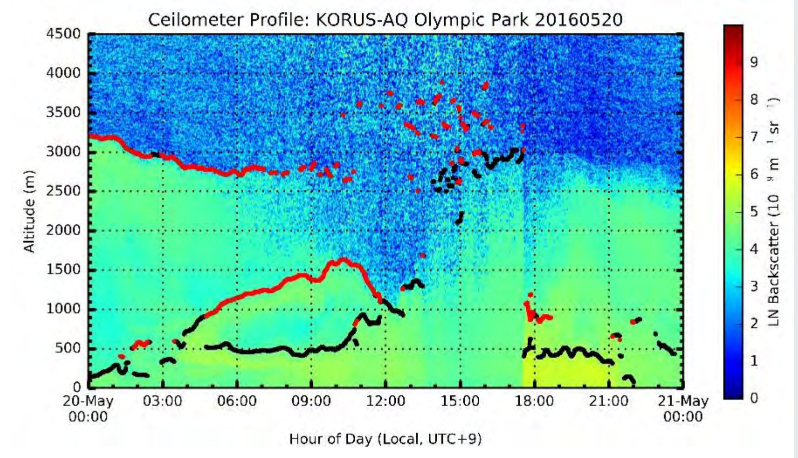
DISCOVER-AQ/FRAPPE (Jul-Aug 2014, Denver, CO)

Low Aerosol Environment



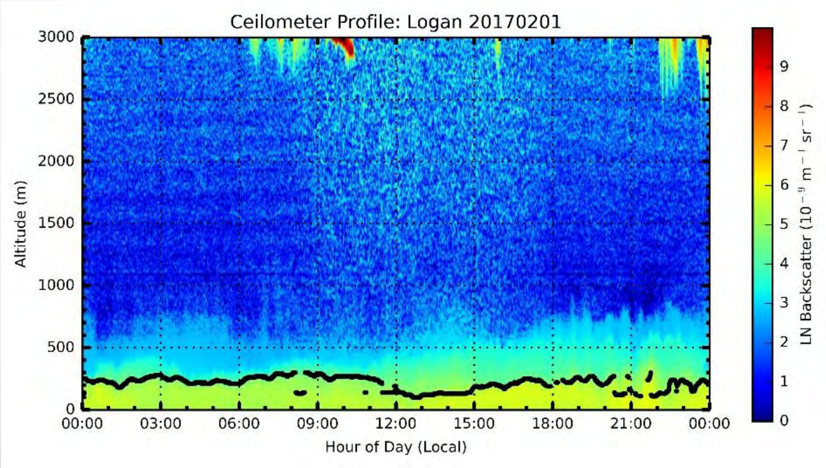
KORUS-AQ (May-Jun 2016, Seoul, S. Korea)

High Aerosol Environment



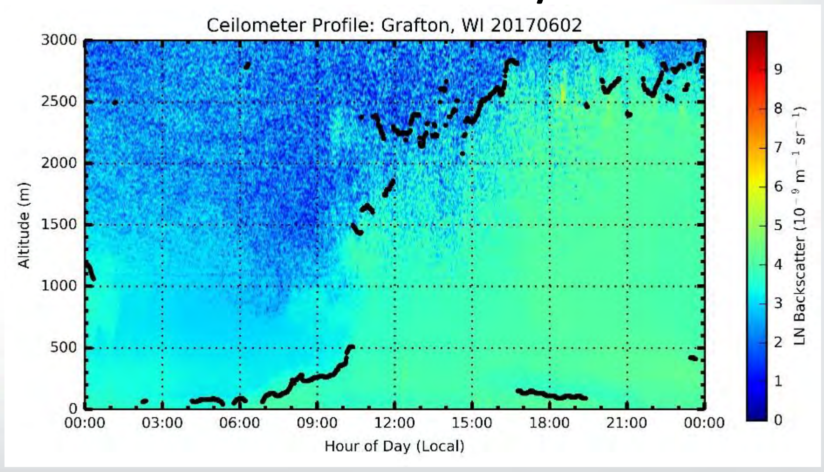
UWFPS (Jan-Feb 2017, Utah)

High Aerosol w/ Cold Pool Inversions



LMOS2017 (May-Jun 2017, Lake Michigan, WI/IL)

Low –Moderate Aerosol Land/Water Interface



Outputs/Products (2014-2017): Demonstrate utility of advance measurement technology relative to NAAQS existing measurement methods

– August 2016 issue of EM contained a complementary series of articles which highlighted research under ACE EM spanning traditional NAAQS FRM/FEM research (EM1.6) and Sensor and Remote Sensing (EM3.3) conducted in an integrated fashion.

1. *Evaluation and Comparison of Methods for Measuring Ozone and Nitrogen Dioxide Concentrations in Ambient Air during DISCOVER-AQ* – Long et al.

2. *Use of Air Quality Sensors during DISCOVER-AQ* – Duvall et al.

3. *The Use of Lidar Technology for Measuring Mixing Heights under the Photochemical Assessment Monitoring Stations (PAMS) Program* – Szykman et al.

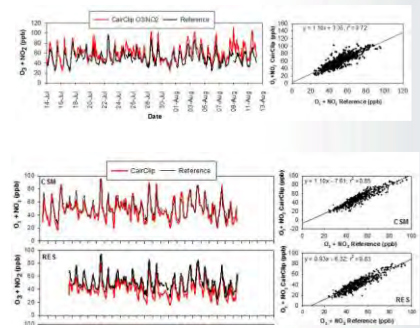
4. *Multi-Perspective Observations of Nitrogen Dioxide over Denver during DISCOVER-AQ: Insights for Future Monitoring* – Crawford, Long, Szykman et al.


sensors

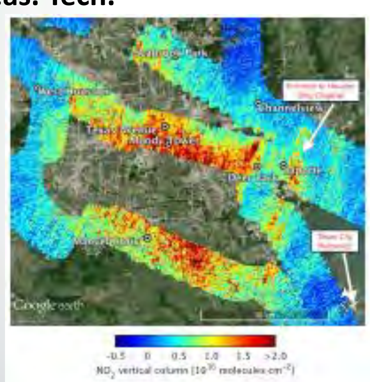
Article

Performance Evaluation and Community Application of Low-Cost Sensors for Ozone and Nitrogen Dioxide

Use DISCOVER-AQ deployments to evaluate performance of low-cost sensors and their feasibility in a citizen science-operated network. Published in *Sensors* (Oct 2016).

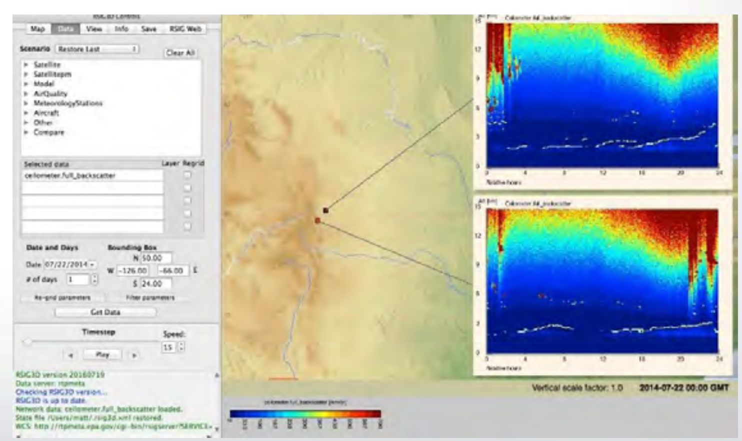


Use of DISCOVER-AQ measurements to assess spatial gradients of NO_2 at urban-scales published in Atmos. Meas. Tech.



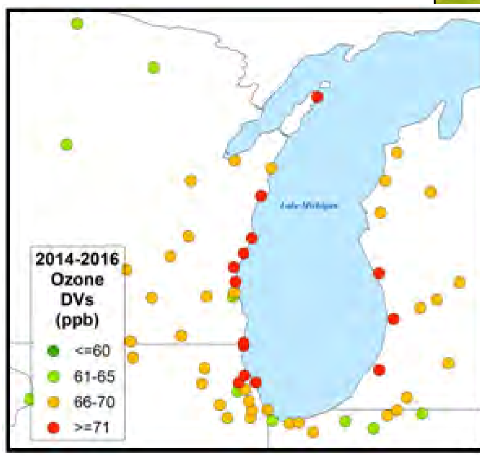

Nitrogen dioxide observations from the Geostationary Trace gas and Aerosol Sensor Optimization (GeoTASO) airborne instrument: Retrieval algorithm and measurements during DISCOVER-AQ Texas 2013

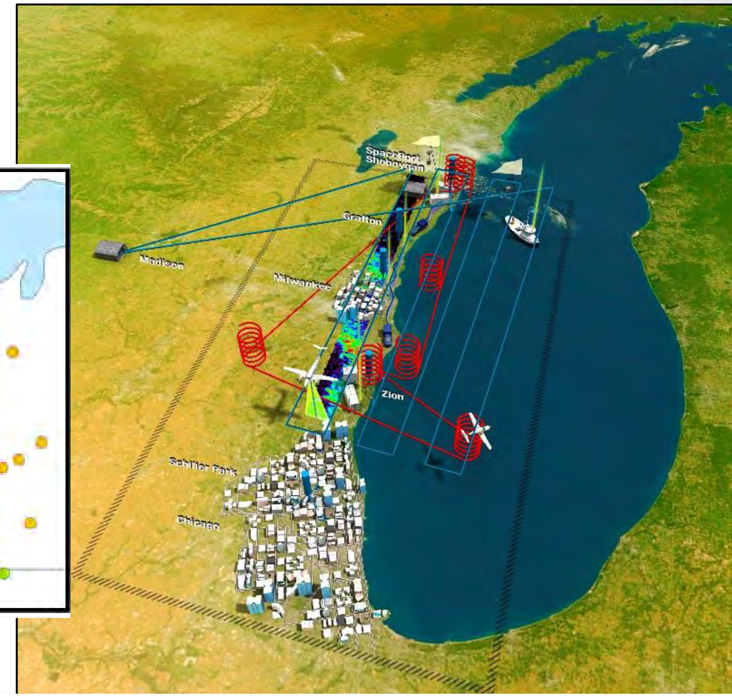
Integrating Field Measurements, Advance IT Architecture and Tools to demonstrate PAMS-relevant Prototype for future ceilometer data.



Lake Michigan Ozone Study (LMOS) 2017
May 22nd-June 22nd 2017

- **Multi-agency collaborative study involving aircraft-, ground-, and ship-based measurements as well as chemical and meteorological models**
- **Motivated by the numerous O_3 NAAQS exceeding monitors along the shore of Lake Michigan influenced by the lake breeze (red dots to the right)**
- **Use Study to Investigate/Demonstrate how new measurement technology (including satellites) can better inform emission patterns, transport, and exposure through integrated column/surface measurement strategy.**





Goals:

1. Understand lakeshore gradients in ozone concentrations and how **regional emissions and lake-breezes** influence ozone pollution in this region
2. Help define chemical model needs for LADCO and states and EPA to meet O_3 NAAQS

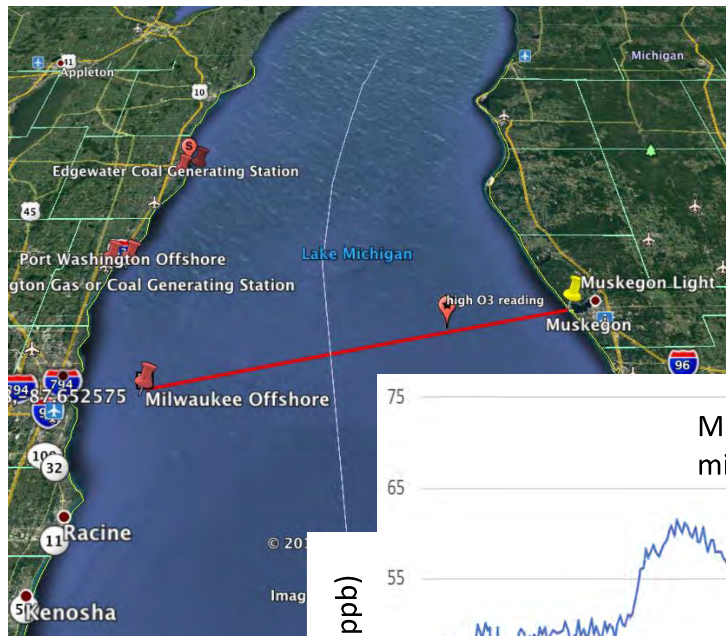
Funding Sources: EPA, NASA, NSF, NOAA, EPRI, and LADCO

Participating agencies: EPA, NASA, NOAA, Scientific Aviation, U. Wisconsin, U. Iowa, U. Minnesota, U. Northern Iowa, UMBC, LADCO, WDNR, IEPA, IDEM

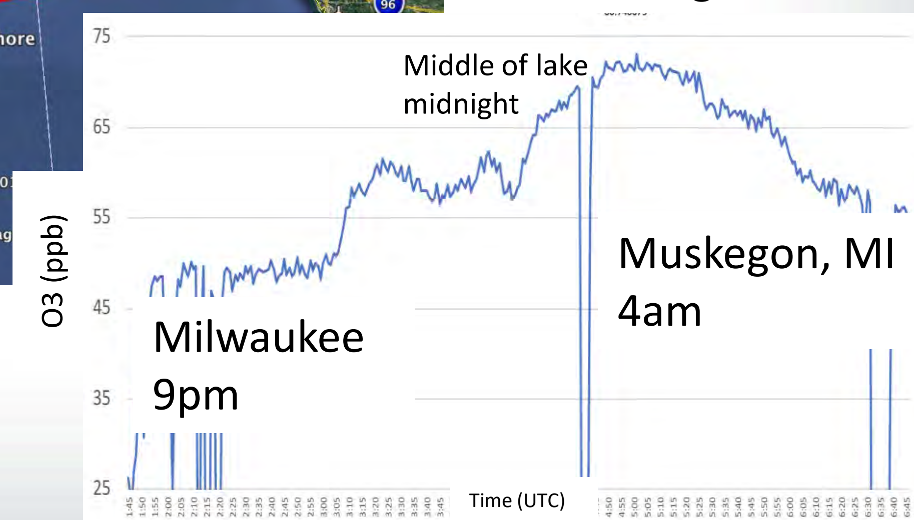
LMOS 2017 Public Data Archieve:
https://www-air.larc.nasa.gov/missions/lmos/index.html

LMOS shipboard measurements

- **Ship based measurements of trace gases were used to track the movements of O3 and NO2 along the Lake Michigan coast**
- **Data was often collected concurrently with airborne measurements**



Shipboard measurements verified model predictions of high O3 over the lake at night



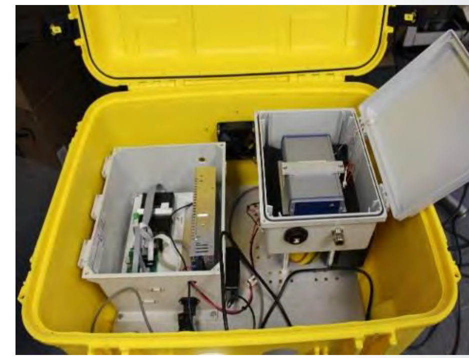
EPA-NASA Collaboration under Pandora Global Network (PGN)

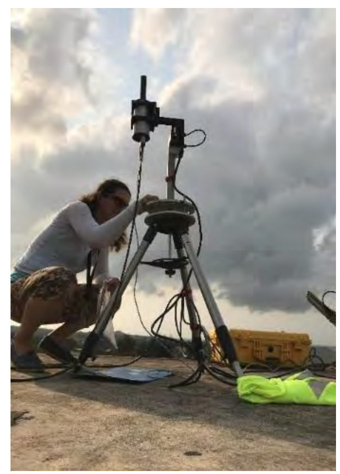
- EPA is working with the NASA Pandora Project to develop a subset surface air quality sites to host Pandora spectrometer instruments and contribute to larger Pandora Global Network.
- Initial focused is use of Pandora as an Enhanced Monitoring Instrument under the re-designed PAMS and also CASTNet site.
- Field missions used to evaluate pandora performance and retrieval for air quality applications and satellite validation (TROPOMI & TEMPO). Research showed pandora highly relevant to air quality and ability to provide relevant observations for key O_3 precursors of NO_2 and HCHO.
- Pandora Project strategy informed by those campaigns is to tie measurements to US AQ network and leverage existing logistical and observational infrastructure
- Initial deployment ~12 long-term instrument across the Ozone Transport Region April/May 2018.
- NASA Pandora Project is a collaboration with ESA through Luftblick currently developing the Pandonia Global Network (PGN) to provide global community with standardized and validated long-term AQ and AC observations to support ground-based, in-situ and satellite missions

I thought Pandora was a music service?

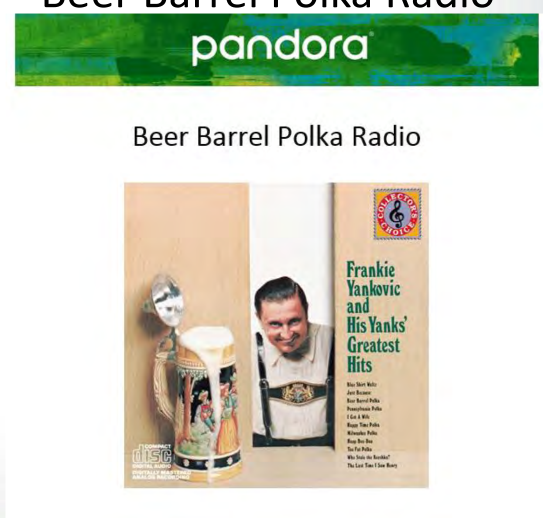
Pandora Ground-Based Spectrometer

- System developed at NASA Goddard
- Ground-based direct sun/moon & sky scanning remote sensing for air quality and atmospheric composition (1S - ~270 – 530 nm, 0.6 nm; 2S – 400 – 900 nm, 1 nm) provides slant column measurements.
- NRT Standard Operational Products at high frequency (~ 2 mins): Total Column Ozone (+/-15 DU, ~5%); Total Column NO2 (+/-0.05 DU, ~10%)
- Additional non-validated products: HCHO - Total column, trop. & near sfc; NO2, O3 – trop. & near sfc
- Successfully deployed for multiple field campaigns (e.g. DISCOVER-AQ, KORUS-AQ, LMOS and OWLETS) as well as long-term monitoring.
- 2 main parts to instrument – (1) sensor head and (2) spectrometer, TE cooler, electronics, computer contained with environmental housing case 23”x16”x39” or 8” rack mounted enclosure.
- Requires at least 1 month of operations at a given site to build calibrations before realtime data availability



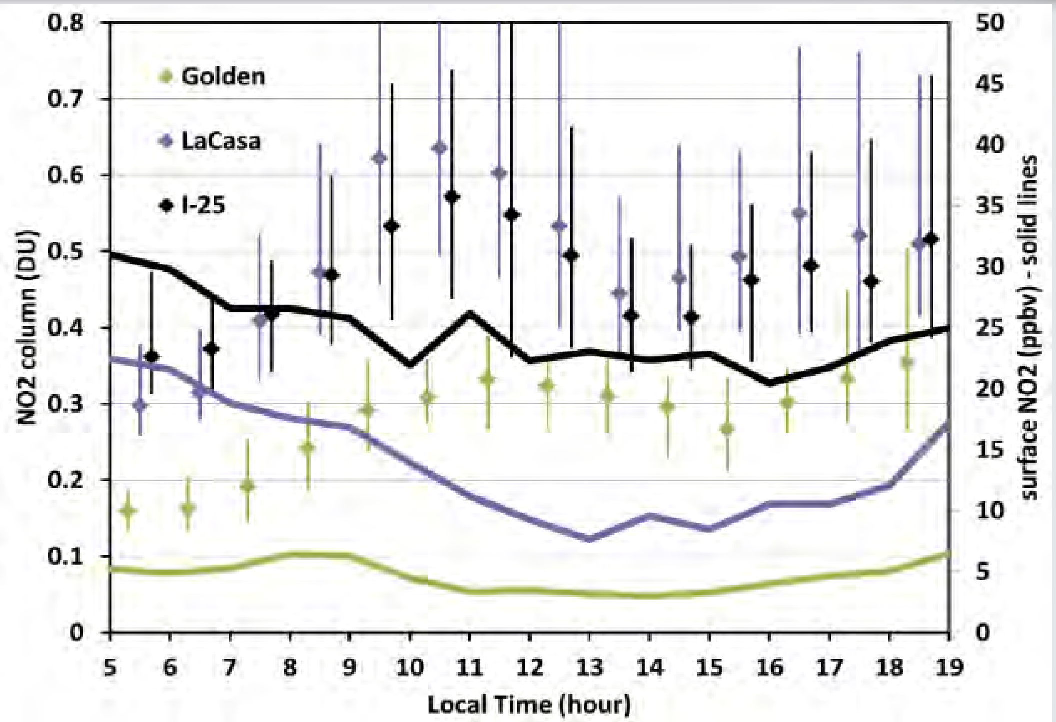


“Ease into Monday with Beer Barrel Polka Radio”



DISCOVER-AQ NO_2 Column and Surface during Denver Campaign (July-August 2014)

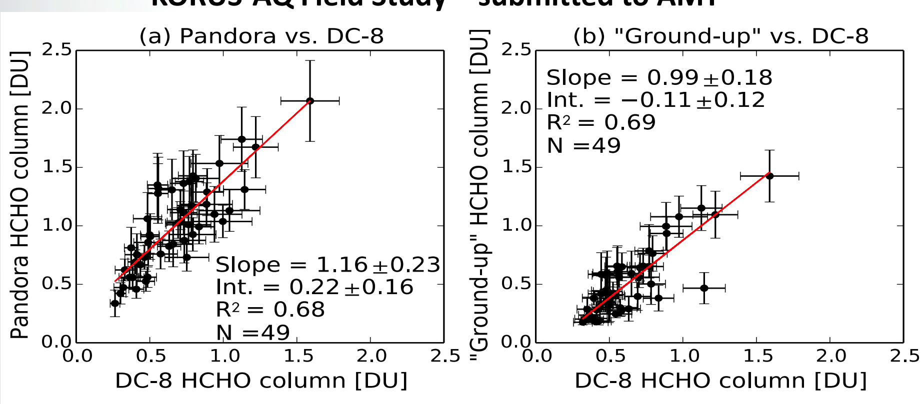
- Pandora Colum NO_2 observations provide a measurement on diurnal column variations.
- Over a regional domain the combination of surface and column NO_2 provide can provide an improved ability to better characterize sources, mechanisms, pollutant transport, and the evolving air chemistry.



Diurnal variation of NO2 column and surface concentrations for three locations in the Denver area during the DISCOVER-AQ campaign. Symbols indicate median values and inner quartile range observed by Pandora spectrometers at each location during the study period. The solid lines indicate median values throughout the day observed by surface monitors. (Crawford et al., 2016)

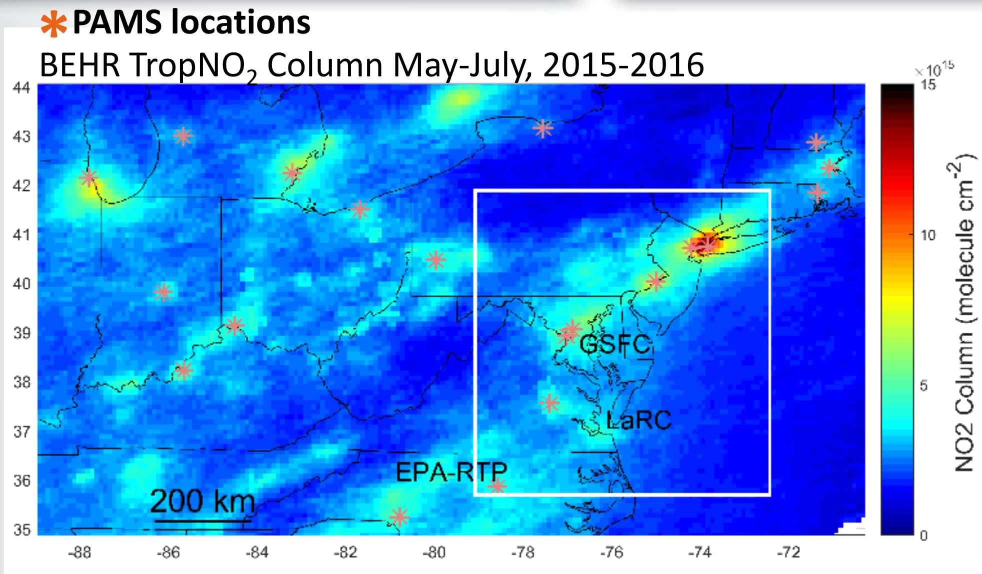
KORUS-AQ Evaluated pandora HCHO Column Retrieval (May-Jun 2016)

Spinei, E., A. Whitehill et al., The First Evaluation of Formaldehyde Column Observations by Pandora Spectrometers during the KORUS-AQ Field Study – submitted to AMT



- Recent improvements in Pandora design have addressed several technical issues.
- The KORUS-AQ campaign provided EPA-ORD and NASA a critical set of ground and aircraft measurements to evaluate formaldehyde (HCHO) from the pandora instrument.
- **Preliminary results show the pandora spectrometer or combination of in-situ (surface) HCHO+ceilometer for mixing height can be used to validate satellite-based HCHO columns from instruments such as TropOMI or TEMPO!**

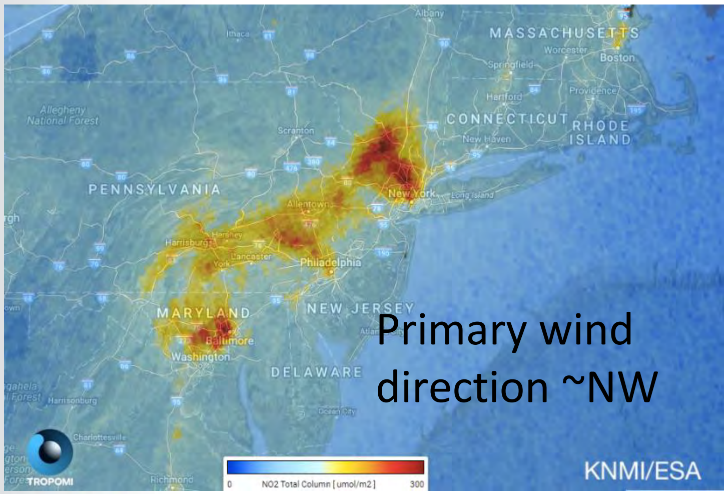
A Select Number of EPA and NASA Pandora Spectrometers will support the new PAMS Enhanced Monitoring Plans within the Ozone Transport Region



- PAMS-EMP/Pandora effort – Initial Deployment April/May 2018:
  - Column measurements to support an improved assessment of emissions, chemistry, and dynamical processes driving ozone issue via daytime diurnal profiles of NO2/HCHO in conjunction with other measurement suite.
  - **Satellite validation TROPOMI & TEMPO** – drawing a better connection between satellite columns and surface air quality, increasing value for end users.
- Leverages collocated PAMS “True” NO2, continuous mixing height, and future continuous HCHO.
- Provides a sustainable low cost approach that mutually increases the value of measurement suite at these sites and supports states EMPs.

Making an Improved Connection between Satellite Columns and Surface Air Quality

TROPOMI First Light: NO_2 NE U.S. Europe



TROPOMI First Light: Power Plants over India

- European Space Agency launched TROPOMI on October 2017. Will provide derived tropospheric columns of NO_2, HCHO, SO_2, plus other species.

- Unprecedented observations of Tropospheric NO2 on a daily basis. Global Coverage 1 day - TropNO_2 3.5 km x 7 km ~13 times improved spatial resolution over OMI.

- PAMS-Pandora EMP Network will provide measurements to draw a better connection between satellite-and-surface air quality for NO_2 and HCHO while providing valuable measurements for satellite validation.

- Anticipate initial release of public data products in summer 2018.

- EPA-ORD team part of TROPOMI validation team.

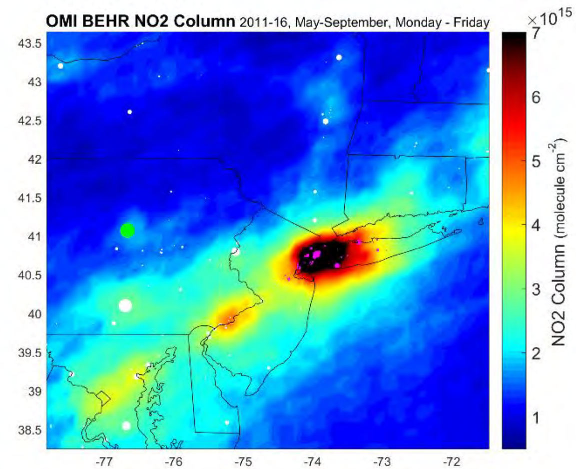
Long Island Sound Study of Ozone (LISSO) 2018

June-August 2018

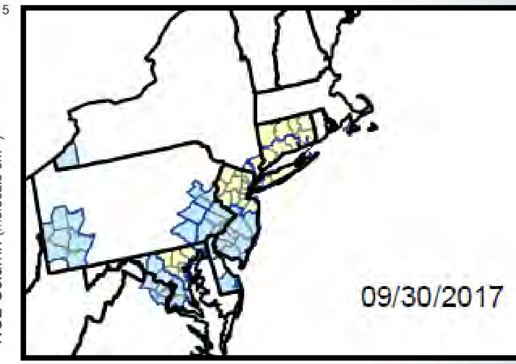
Goals:

1. Better understand the specific features of ground-level ozone photochemical formation and transport downwind of NYC over Long Island Sound that are responsible for on-going violations of national ozone air quality health standards.
2. Understand nearshore gradients in ozone concentrations and how regional emissions and sound-breezes influence ozone pollution in this region
3. Integrate large remote sensing component via GeoTASO, PANDORA at PAMS site, and TROPOMI to improve of understanding of NO2 and HCHO distributions of the region.
4. Help define chemical model needs for NESCAUM and states and EPA to meet O_3 NAAQS.
5. Investigate the future implications of wildfire plumes originating from distant locations on the Northeast's air quality as local and regional anthropogenic emissions continue to decline Largest Ozone Events tied to smoke transport..

The NYC-LIS NO_2 Volcano as seen from satellite (OMI)



NE O3 non-attainment areas 8-hr 0.075 ppm



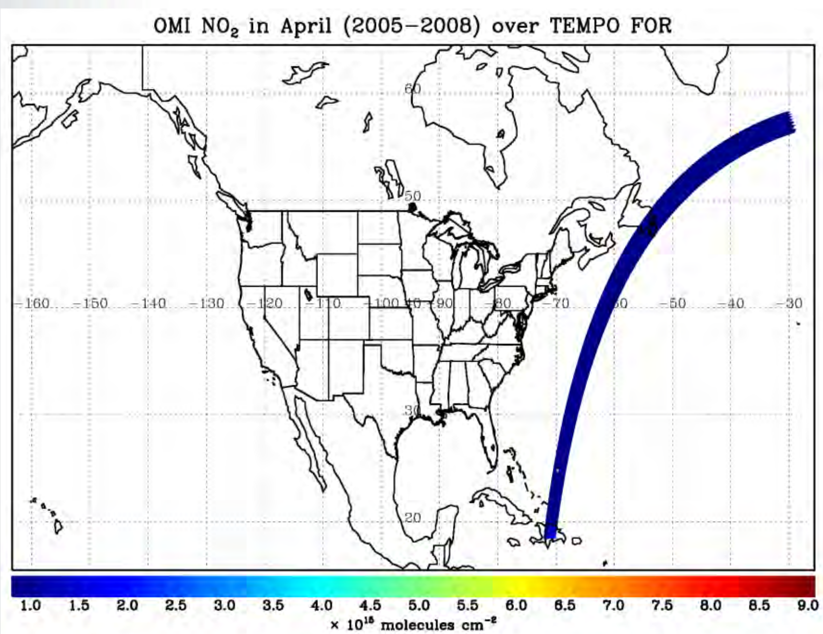
Multi-agency collaborative Study:

EPA, NASA, NOAA, UMD, Suny Albany, CCNY, CTDEEP, NJDEP, NYDEC

Tropospheric Emissions: Monitoring of Pollution (TEMPO) Geostationary Mission– Cira 2020

NASA Selected Earth Venture Instrument (2102)
PI- Kelly Chance, Smithsonian Astrophysical Obs.
Instrument Development: Ball Aerospace
Project Management: NASA LaRC
Other Institutions: NASA GSFC, EPA, NCAR, Harvard, UC Berkeley, St. Louis U, U Alabama Huntsville, U Nebraska, RT Solutions, Carr Astronautics
International collaboration: Mexico, Canada, Cuba, Korea, U.K., ESA, Spain

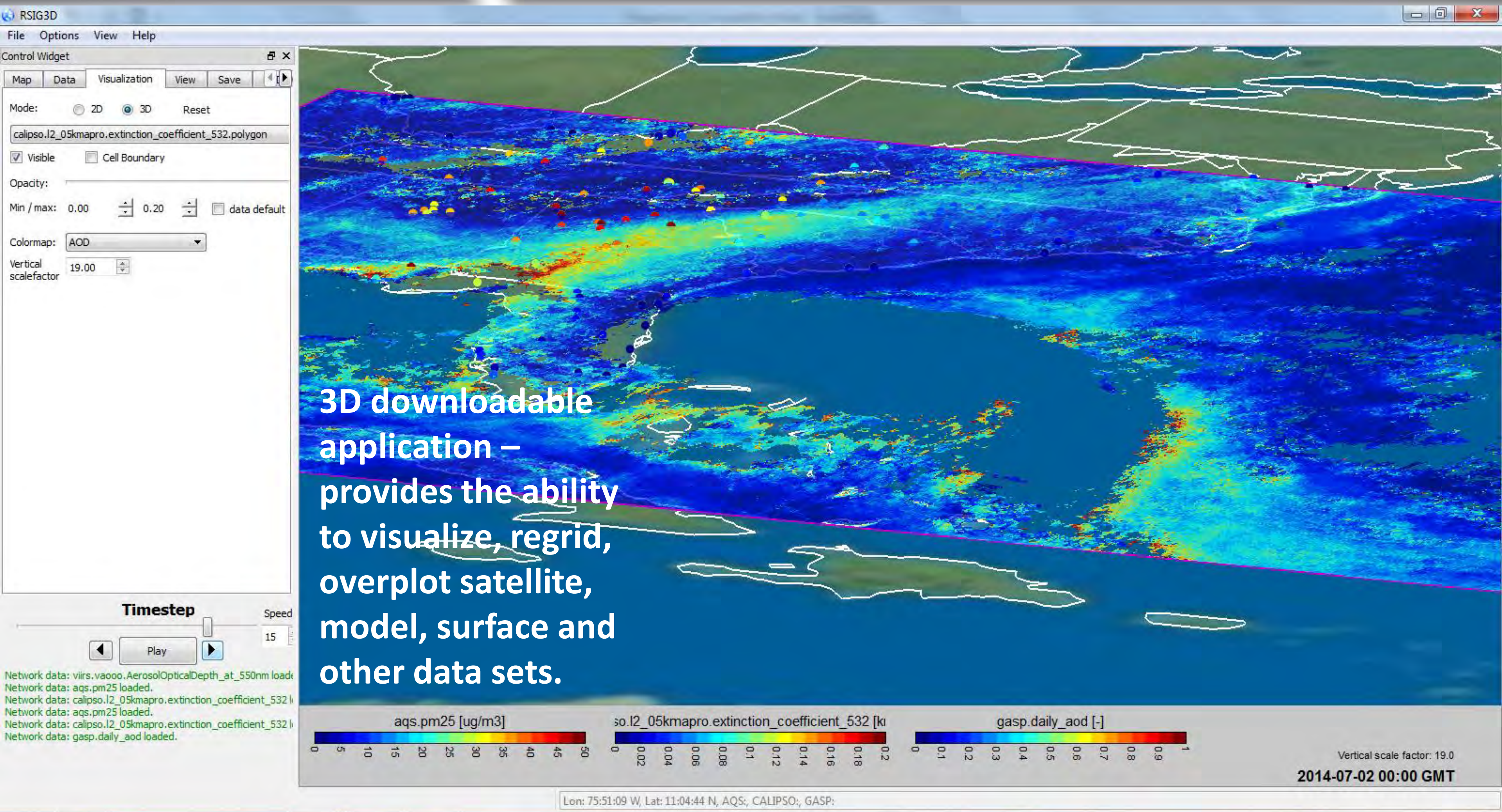
Species/Products	Required Precision	Temporal Revisit
0-2 km O_3 (Selected Scenes) Baseline only	10 ppbv	2 hour
Tropospheric O_3	10 ppbv	1 hour
Total O_3	3%	1 hour
Tropospheric NO_2	1.0×10^{15} molecules cm^{-2}	1 hour
Tropospheric H_2CO	1.0×10^{16} molecules cm^{-2}	3 hour
Tropospheric SO_2	1.0×10^{16} molecules cm^{-2}	3 hour
Tropospheric $C_2H_2O_2$	4.0×10^{14} molecules cm^{-2}	3 hour
Aerosol Optical Depth	0.10	1 hour



- Minimal set of products sufficient for constraining air quality
- Across Greater North America (GNA): 18°N to 58°N near 100°W, 67°W to 125°W near 42°N
- Data products at urban-regional spatial scales
- Temporal scales to resolve diurnal changes in pollutant distributions
- Collected in cloud-free scenes
- Mission duration, subject to instrument availability
  – Baseline 20 months
  – Threshold 12 months

tempo.si.edu

U.S. EPA Remote Sensing Information Gateway: Collaborative Advance Computing Infrastructure and Application involving NASA, NOAA, and Universities



www.rsig.epa - Getting Data to the End User

State of Sensor Science
Wildland Fire Sensor Challenge

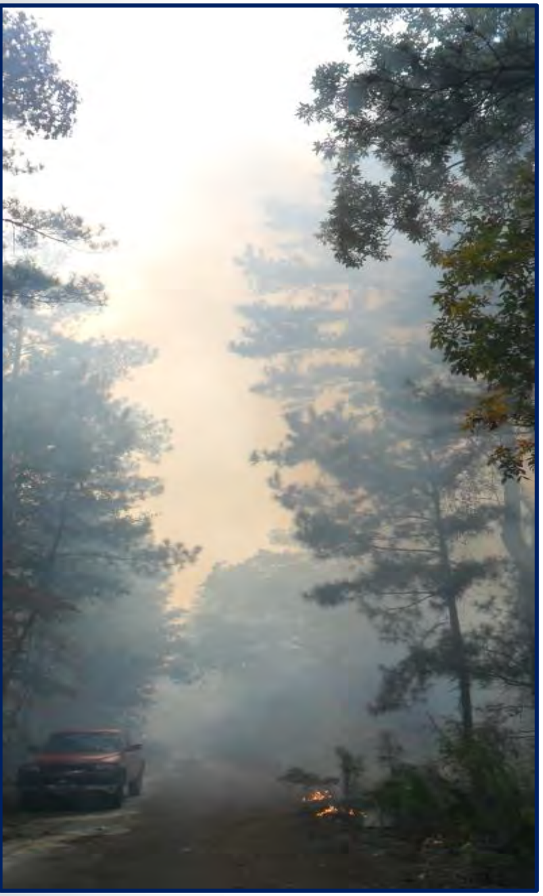
https://www.challenge.gov/challenge/wildland-fire-sensors-challenge/

Matthew Landis

Collaborators

- **EPA ORD\NERL Air Quality Branch <u>Wildland Fire Research Team</u> Members**
  - Russell Long, Jonathan Krug, Mohammed Jaoui, Maribel Colon, Andrew Whitehill, Surender Kaushik
- **ACE Program Staff**
  - Kirk Baker, Gayle Hagler
- **U.S. Forest Service Rocky Mountain Research Station**
  - Shawn Urbanski
- **ORD Office of Assistant Administrator**
  - Gail Robarge, Stacey Katz
- **Innocentive (Contractor)**
  - Michael Albarelli, Catherine Covington

Wildland Fire Sensor Challenge



Shared vision by partnering organizations:

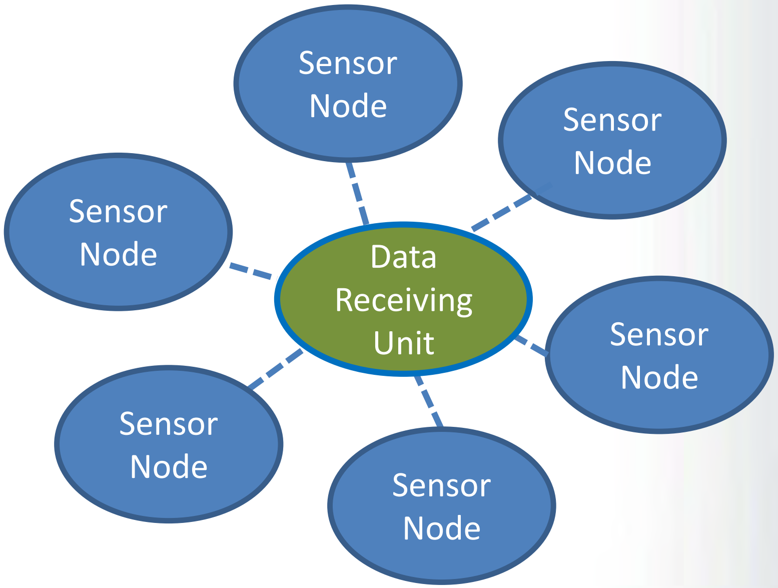
A desire to advance air measurement technology to be **easier to deploy**, suitable to use for **high concentration events**, **durable** to withstand difficult field conditions, and report data **continuously and wirelessly**. Desired measurements: $PM_{2.5}$, O_3, CO, CO_2.

Partnering federal organizations:

Wildland Fire Sensor Challenge

Challenge Specifications:

- The collaborating partners developed challenge criteria to encourage development of prototype sensor nodes capable of rapid deployment and continuous real-time monitoring of highly dynamic air pollution levels during a fire event.
- $PM_{2.5}$, CO, and O_3 of concern for human health, CO_2 is useful information to track fire behavior
- In addition to measuring 4 pollutants, the system should also be easy to use, self-powered, include location data, and wirelessly transmit data to a central data-receiving station



Challenge: Target Measurements

- Target measurement ranges are shown at right - the large range identified for all parameters is related to the dynamic concentration levels that may be experienced.
- Each node must provide geo-location (latitude and longitude) information along with the measurement data
- Solvers will not be disqualified if these targets are not exactly met – the target ranges should be considered as goals to aim towards.

Pollutant	Target lower / upper detection limit
$PM_{2.5}$	10 / 1500 µg m^{-3}
CO	1 / 500 ppm
O_3	20 / 200 ppb
CO_2	350 / 10,000 ppm

Metric	Target
Accuracy	20%
Linearity	20%
Precision	20%
Calibration Error	10%
Operability / Durability	Qualitative

Wildland Fire Sensor Challenge

Schedule and Award

Key Deadlines for Solvers:

- Written preview of solution (Nov 22, 2017)
  - ➢ 27 solver applications were received
- Shipping of prototype sensor system for testing (Jan 18, 2018)
  - ➢ 17 solvers were selected for submission of prototypes for testing

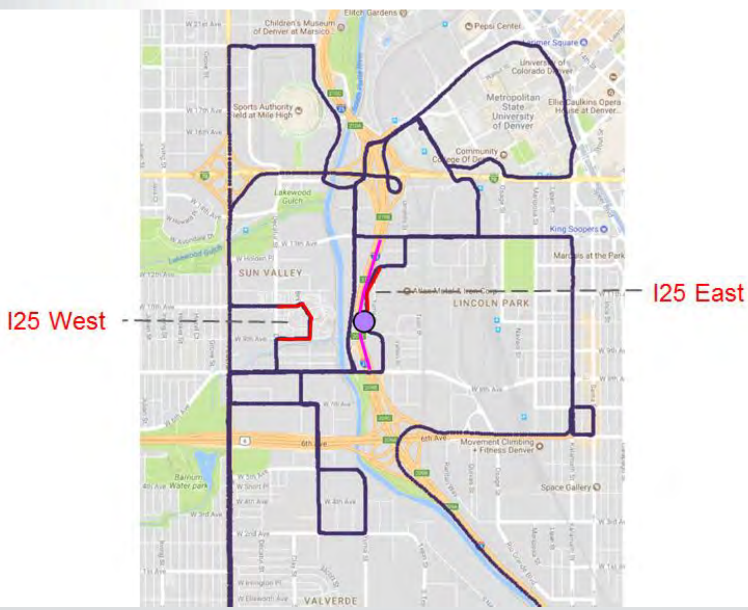
Next Steps

- Complete Phase I Testing – EPA, RTP March 2018
- Complete Phase II Testing – EPA/USFS, Missoula May 2018
- Award Prize(s) – Summer 2018
- Field Testing on Wildland Fires – Summer/Fall 2018
- EPA Report/Scientific Publication – Fall 2018

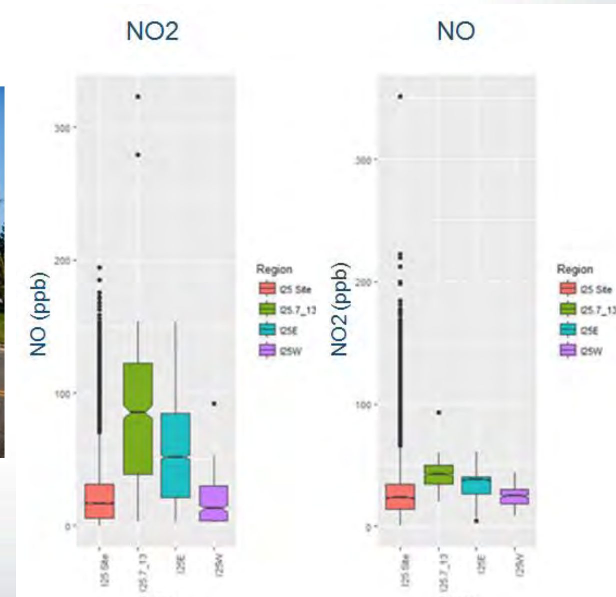
State of Sensor Science

EPA-Aclima CRADA - Mobile Monitoring

Paul A. Solomon
Surender Kaushik



Google street view car with monitors.



Collaborators

- Andrew Whitehill (ORD)
- Matthew Small (Region 9, RSL)
- Dena Vallano (Region 9)
- Colby Tucker (Region 9)
- Shea Caspersen (Region 9)
- Melissa Lunden (Aclima)
- Brain LaFranchi (Aclima)
- Ashok Singh (ADI-NV INC)
- Electric Power Research Institute
  - Charlie Blanchard (Envair)

Project Overview

To develop an scalable mobile monitoring platform measuring concentrations of gas and particle phase pollutants at the hyperlocal level and very high time resolution, providing individuals and communities as well as researchers information needed to better understand air pollution variability and exposure on small spatial scales in real time.

NO2 Concentrations in San Francisco, CA based on Mobile Measurements

Ongoing Efforts

- Continue analysis of the hyperlocal data collected in Denver and throughout California.
- Continue to work with Aclima on other parts of the CRADA, including:
  - Developing and evaluating low-cost state-of-the-art sensors
    - PMf, PMc, PM10 mass
    - Black carbon

State of Sensor Science

Data Fusion Modeling to Improve the Prediction of Air Quality

David M. Holland

Collaborators

- –Lucy Lu, Duke University/Statistics
- –Alan Gelfand, Duke University/Statistics
- –Erin Schliep, University of Missouri/Statistics
- –Veronica Berrocal, University of Michigan/Biostatistics
- –Colin Rundel, Duke University/Statistics

Project Overview

- Establish National Real-Time Ozone Forecasting
  - Develop a real-time operational fusion model to forecast 8-hr avg O_3
  - Uses real-time monitoring data and eta-CMAQ numerical model output
- Predict Speciated $PM_{2.5}$ components over the U.S. (Completed)
  - Uses weekly average speciated data from 3 networks and CMAQ output
  - Improved predictions in comparison to interpolating just the monitoring data
- Predict spatial patterns of $PM_{2.5}$ using VIIRS satellite and ground monitoring data (Completed)
  - Can we quantify any predictive improvement of $PM_{2.5}$ using VIIRS satellite data
  - Using data in summer (2013), very little improvement was found

Project Overviews (Cont'd)

- Develop Fused Predictive Surfaces (O_3 and $PM_{2.5}$) web site with OAQPS (Completed)
  - Archive daily surfaces for easy retrieval for time period 2002-2014
- Village Green Forecasting (Ongoing)
  - At the Durham, NC site, forecast 8-hr average O_3 concentrations, extend model to other VG sites
  - At Durham, 8-hr forecasts compare well with actual 8-hr average data
- Predict spatial patterns of extreme (annual 4^{th} maximum) O_3 values (Completed)
  - Use fusion models to directly model the 4^{th} max values

Results

- Based on several applications, downscaler fusion models that combine both ground monitoring data and CMAQ numerical output improve spatial prediction in comparison to models based solely on monitoring data
- Real-time forecasting is feasible and practical, these models should be implemented and compare to existing forecast models.
- The downscaler web site has allowed easy access to fused historical prediction, and these daily air quality inputs have been used in many investigations.
- All of these investigations have been published in the peer-reviewed statistical literature

State of Sensor Science
(Infrastructure Supporting Air Sensors)

Vasu Kilaru

Collaborators

- **Kristen Benedict – OAQPS**
- **Ron Williams – ORD**
- **Duane Young – OW**
- **EDF (Environmental Defense Fund)**

Project Overview

- E-enterprise Team 4 – identification of data and metadata standards for air and water sensors for consideration by the EPA. Ongoing areas of research:

I. What data standards currently exist?
II. How widely have they been adopted?
III. How well do the suit EPA needs?
IV. What elements are most important to EPA?
V. What is the recommended approach?

Project Overview

Air Sensors Working group (ASW) represents a broad coalition of stakeholders (EPA, State, academia, and sensor manufacturers)

I. Adopt and advocate for data and metadata standards for air sensors

II. Develop a "cloud" service for users to upload, analyze, visualize, and freely share air sensor data

Results

- **E-enterprise Team 4 has submitted its recommendation in a white paper to senior leadership**
- **ASW is close to having a "alpha" version of the "cloud" service for review in early 2018**

Next Steps

- **Based on E-enterprise leadship team recommendation, Team 4 will likely be charged with further research into implementation of a data/metadata standards along with identification of metadata elements for inclusion into the standard.**
- **ASW after release of the "cloud" service, will delve into data/metadata standards for the external sensor community.**

Measurement Methods to Inform Communities

Rich Callan
ORD-NCER

Research Questions

Solicitation: "Air Pollution Monitoring for Communities," EPA Science to Achieve Results (STAR) Program

1. How to **measure air pollution levels** at the individual and community level?

2. How to **maximize value of sensors for communities** and how to **share information** effectively?

3. How to interpret **data quality** from sensors? How well do sensors perform **over time?**

4. Can we **map patterns of air pollutants over space and time** using sensor networks?

Substantial engagement with community groups was encouraged in the solicitation.

Grantees (EPA STAR Program)

- **Carnegie Mellon University – PI: R. Subramanian, co-PIs: Julie Downs, Spyros Pandis, Albert Presto**
- **Kansas State University/University of Memphis – PI: Wendy Griswold**
- **Massachusetts Institute of Technology – PI: Jesse Kroll, co-PI: Colette Heald**
- **Research Triangle Institute – PI: Seung-Hyun Cho, co-PI: Lisa Cicutto, National Jewish Health**
- **South Coast Air Quality Management District – PI: Andrea Polidori**
- **University of Washington – PI: Catherine Karr**

3-year grants funded in 2016 – can apply for no-cost extensions

Projects and Field Site Locations

1. Carnegie Mellon University:
   Democratization of Measurement and Modeling Tools for Community Action on Air Quality, and Improved Spatial Resolution of Air Pollutant Concentrations – Pittsburgh, Pennsylvania

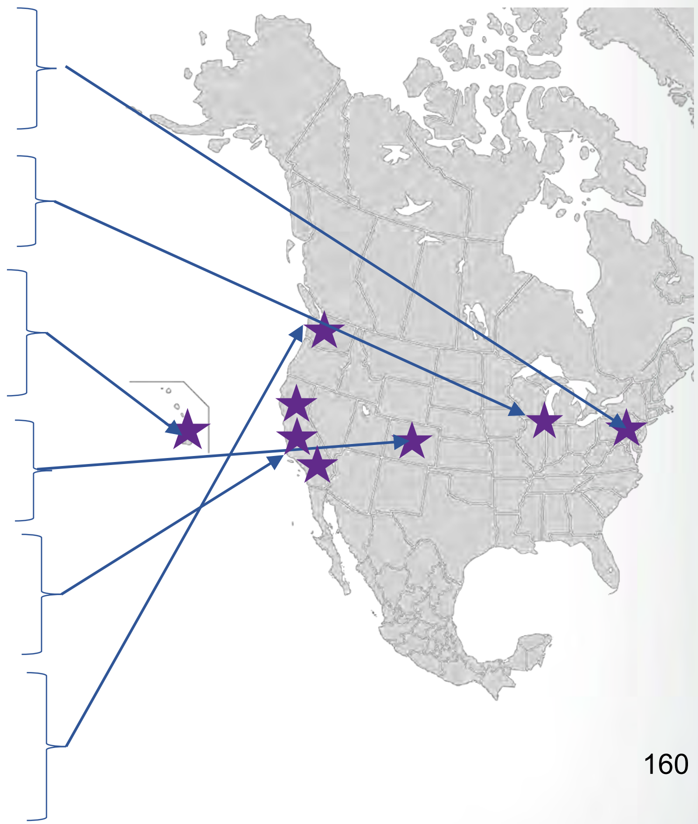
2. Kansas State University
   Shared Air/Shared Action (SA^2): Community Empowerment through Low-Cost Air Pollution Monitoring – Chicago, Illinois

3. Massachusetts Institute of Technology
   Hawai'i Island Volcanic Smog Sensor Network – Hawai'i Island, Hawaii

4. RTI International
   Monitoring the Air in Our Community: Engaging Citizens in Research – Globeville, Elyria Swansea (GES), Denver, Colorado

5. South Coast Air Quality Management District
   Engage, Educate, and Empower California Communities on the Use and Applications of Low-Cost Air Monitoring Sensors – Northern, Central and Southern California

6. University of Washington
   Putting Next Generation Sensors and Scientists in practice to reduce wood smoke in a highly impacted, multicultural rural setting (NextGenSS) – Yakima Valley, Washington State



Democratization of Measurement and Modeling Tools for Community Action on Air Quality

R Subramanian

R Subramanian (PI), Julie Downs (co-PI), Albert Presto (co-PI), Spyros Pandis (co-PI), Carnegie Mellon University

Partners: Jamin Bogi (Group Against Smog and Pollution, GASP), Myron Arnowitt (Clean Water Fund), Thurman Brendlinger (Clean Air Council)

Julie Downs

Carnegie Mellon University

STAR Grant #RD83628601

Courtesy of R. Subramanian

CAPS Center for Atmospheric Particle Studies

Real-time Affordable Multi-Pollutant (RAMP) monitors

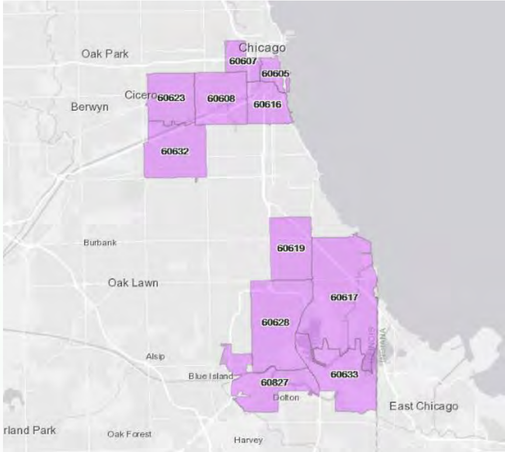
- AlphaSense electrochemical CO, O_3, NO_2, SO_2
- SST CO_2 non-dispersive infrared (NDIR), temp., relative humidity
- Met-One $PM_{2.5}$
- GSM communication to AWS
- Low cost (~$4,500)

Courtesy of R. Subramanian

Shared Air/Shared Action (SA^2): Community Empowerment through Low-cost Air Pollution Monitoring

PI: Wendy Griswold, Univ. of Memphis and Kansas State University

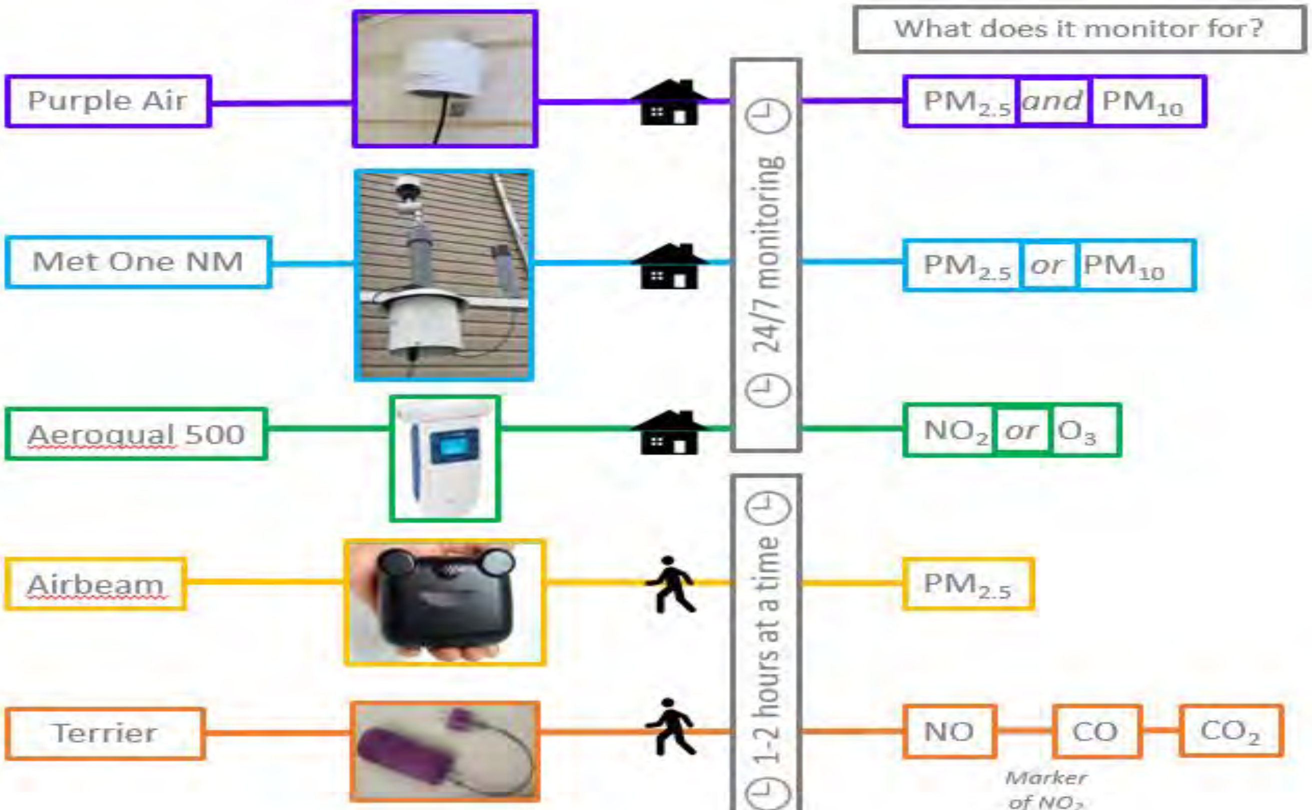
Community Partners Include:
Alliance for a Greener South Loop, Delta Institute, Little Village Environmental Justice Organization, People for Community Recovery, Respiratory Health Association, Southeast Environmental Task Force, University of Illinois-Chicago (UIC)



Target areas for monitoring (ZIP codes)
Little Village:
60623, 60608, 60632
People for Community Recovery:
60827, 60628
Southeast Environmental Task Force:
60617, 60619, 60633
South Loop:
60616, 60605, 60607

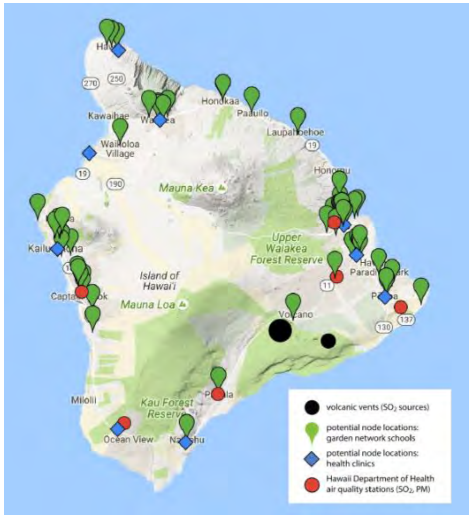
STAR Grant #RD83618201

Sensors for the Shared Air/Shared Action Project



Courtesy of Wendy Griswold

The Hawaiʻi Island Vog (volcanic smog) Network: Tracking air quality and community engagement near a major emissions hotspot



Jesse Kroll
MIT

Colette Heald
MIT

Jesse H. Kroll (PI), Colette L. Heald (co-PI), Kathleen M. Vandiver, Nancy Redfeather, Elizabeth Cole, Ben Crawford

EPA Website:
https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/10741/report/0

MIT Website: http://www.mit.edu/~jhkroll/hawaii/index.htm

Kohala Center Website: http://kohalacenter.org/research/vog-network

MIT Civil and Environmental Engineering | MIT CEHS | THE KOHALA CENTER

STAR Grant #RD83618301

Courtesy of Jesse Kroll

MIT Project – Community Engagement

Meeting with teachers at Kealakehe High School

Standing in back:
Jesse Kroll, Colette Heald
On right seated at table:
Ben Crawford

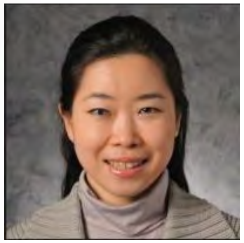
Photo courtesy of Jesse Kroll

Project team (Kroll, Heald, Vandiver, Crawford) traveled to Hawaiʻi in January, 2018

- Held discussions with teachers, health professionals, and community members
- Conducted teacher workshops and meetings at health clinics
- Received offers to “host” sensor nodes

Monitoring the Air in Our Community: Engaging Citizens in Research

Seung-Hyun Cho, RTI International
Lisa Cicutto, National Jewish Health



Seung-Hyun Cho
RTI International
(PI)

Lisa Cicutto
National Jewish Health
(co-PI)

Partner Community:
Globeville, Elyria-Swansea
(GES), Colorado

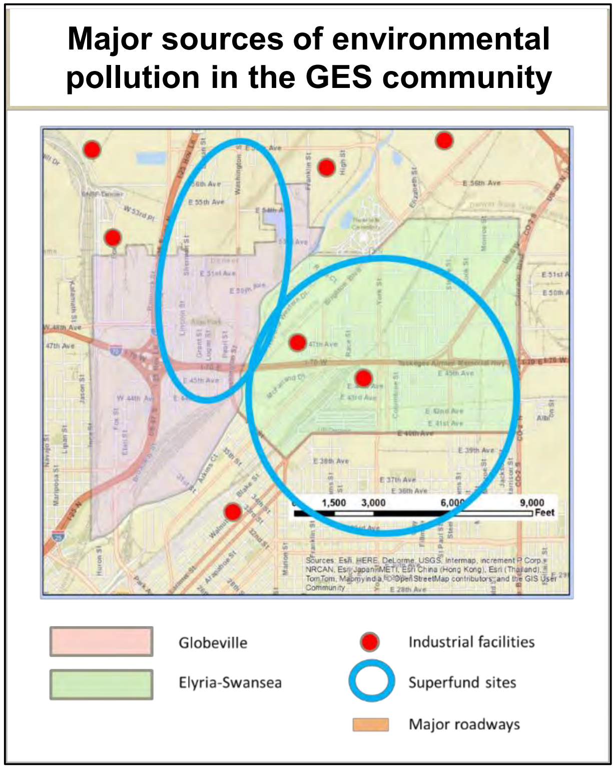
STAR Grant #RD83618701

Courtesy of Seung-Hyun Cho

The Study Community

Globeville, Elyria-Swansea (GES), environmental justice community in north Denver, Colorado

- Higher asthma emergency department visits than Denver average
- Close to 27-square-mile Rocky Mountain Arsenal Superfund site
- Near highly trafficked interstate corridors of I-25 and I-70 (400,000 cars/day)
- Low walkability
- Marginal nonattainment area for ozone (2008-2010)



Courtesy of Seung-Hyun Cho

Engage, Educate and Empower California Communities on the Use and Applications of “Low-cost” Air Monitoring Sensors

STi
Sonoma Technology, Inc.

South Coast AQMD

UCLA

Investigators: Andrea Polidori (Contact PI), Philip M. Fine (co-PI), Laki Tisopulos (co-PI), Yifang Zhu (Co-PI), and Hilary Hafner, STI (Co-PI)

Institutions: South Coast Air Quality Management District (SCAQMD); University of California Los Angeles (UCLA); Sonoma Technology Inc. (STI)

Funding: U.S. EPA STAR Grant #RD83618401

Communities in Northern, Central and Southern California

AQ-SPEC
Air Quality Sensor Performance Evaluation Center
http://www.aqmd.gov/aq-spec

Courtesy of Andrea Polidori

Sensor Deployment across California

Specific aims:

1. Develop educational material for communities
2. Evaluate / identify candidate sensors for deployment
3. Deploy selected sensors in California communities
4. Communicate lessons learned to the public

>150 PM sensors

+100 Aeroqual nodes

(e.g. $PM_{2.5}$, PM_{10}, O_3, NOx)

Cloud-Based Platform Development

- Data storage, visualization and mapping
- Data dissemination

AQ-SPEC

Air Quality Sensor Performance Evaluation Center

http://www.aqmd.gov/aq-spec

Courtesy of Andrea Polidori

Putting Next Generation Sensors & Scientists in practice to reduce wood smoke in a highly impacted, multi-cultural rural setting (NextGenSS)

DEPARTMENT OF ENVIRONMENTAL AND OCCUPATIONAL HEALTH SCIENCES
UNIVERSITY of WASHINGTON
School of Public Health

The Center for Native Health & Culture
@ Heritage University

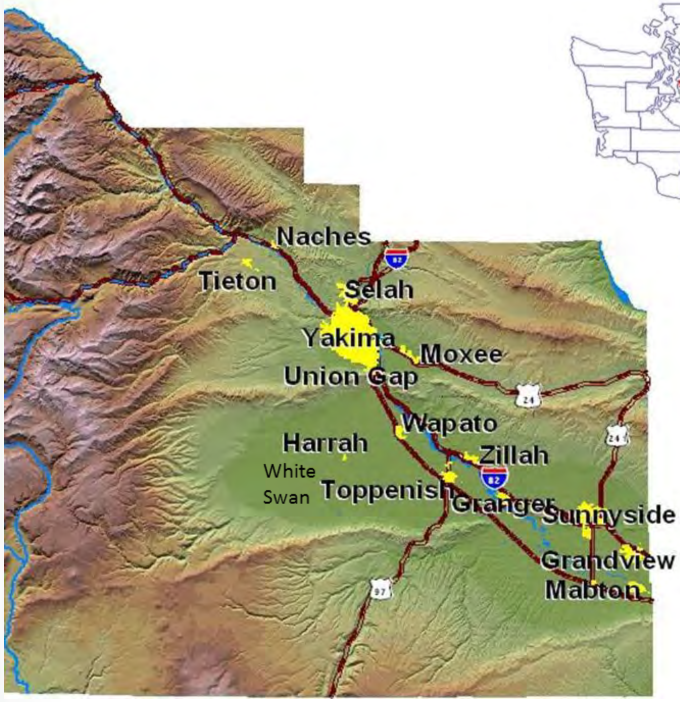
PI: Catherine Karr, University of Washington

Collaboration with
Jessica Black, Heritage University

STAR Grant #RD83618501

Courtesy of Catherine Karr

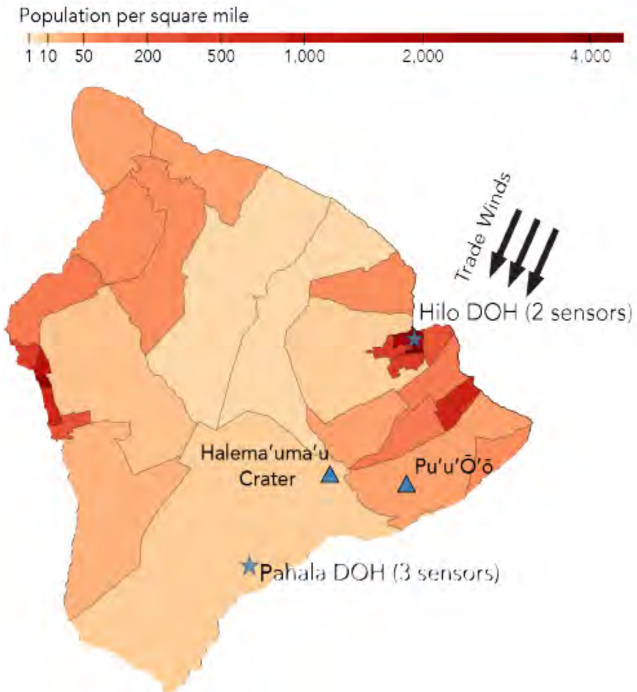
Air Quality and Yakima Valley, Washington State

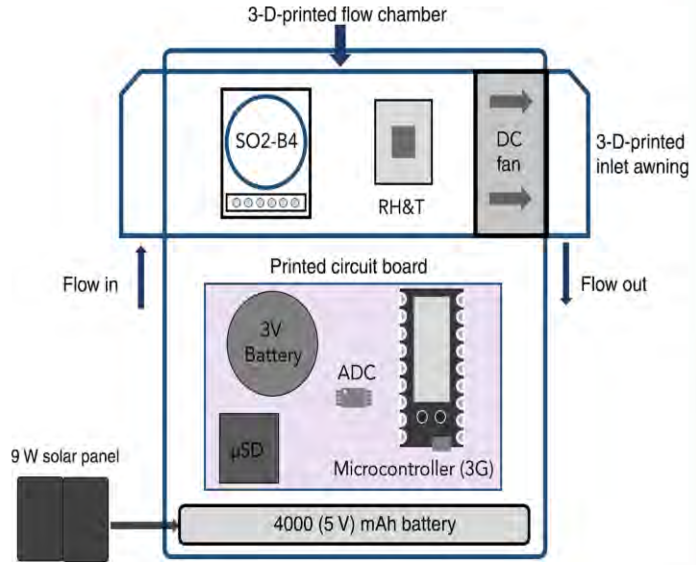


- Air pollution levels (PM) are a concern for many in lower Yakima Valley
- Wood burning is an important contributor
- Impacts are often highly localized (air pollution varies a lot in space and time)
- Limited research on air pollution in rural communities
- Regulatory monitor in Toppenish, White Swan (Yakima)

Courtesy of Catherine Karr

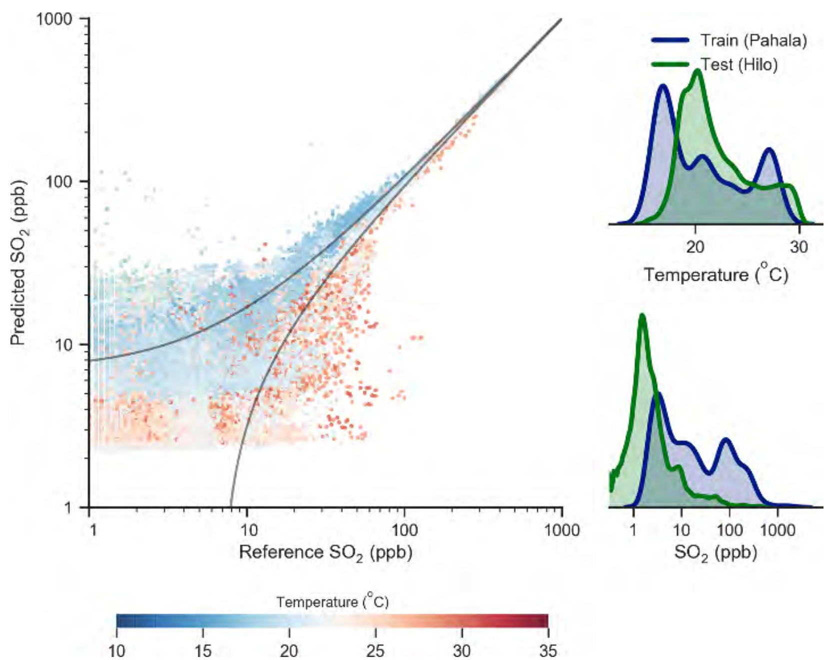
MIT Results 1 – Hagan et al. 2018





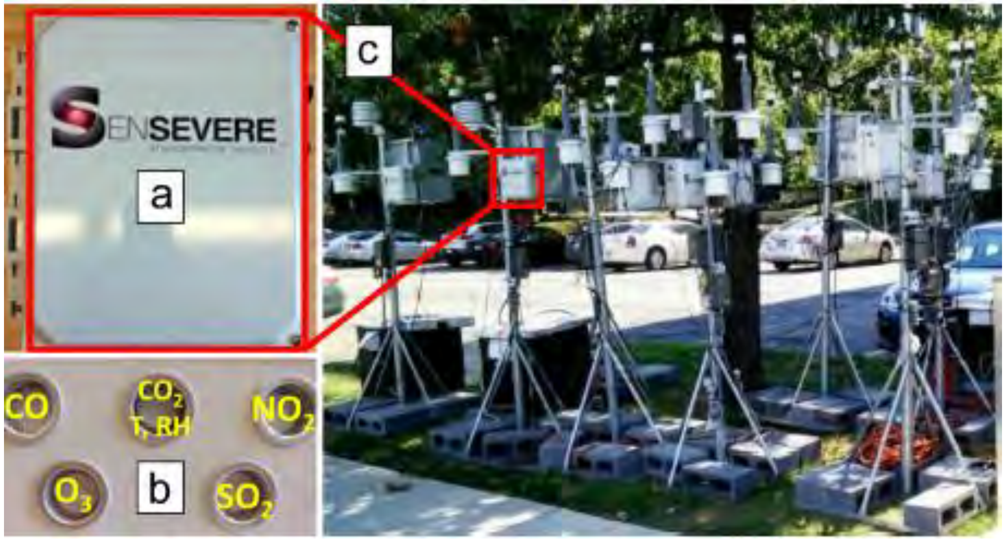
Hagan, D. H., Isaacman-VanWertz, G., Franklin, J. P., Wallace, L. M. M., Kocar, B. D., Heald, C. L., and Kroll, J. H. Calibration and assessment of electrochemical air quality sensors by co-location with regulatory-grade instruments, *Atmospheric Measurement Techniques*, 11, 315-328, January 2018. https://www.atmos-meas-tech.net/11/315/2018/

MIT Results 2 – Hagan et al. 2018



Hagan, D. H., Isaacman-VanWertz, G., Franklin, J. P., Wallace, L. M. M., Kocar, B. D., Heald, C. L., and Kroll, J. H. Calibration and assessment of electrochemical air quality sensors by co-location with regulatory-grade instruments, *Atmospheric Measurement Techniques*, 11, 315-328, January 2018. https://www.atmos-meas-tech.net/11/315/2018/

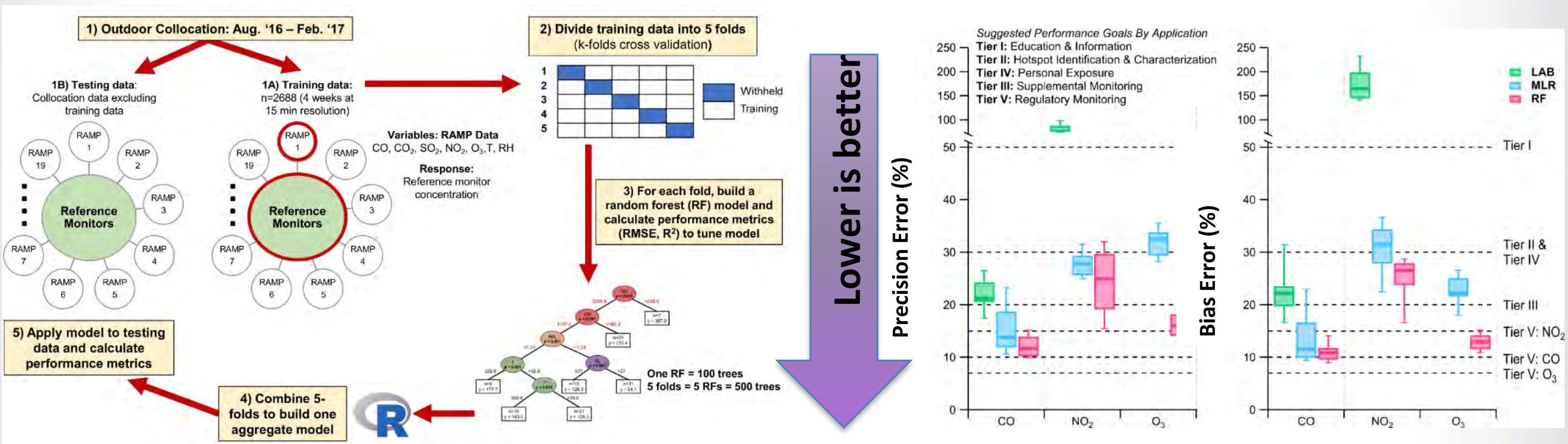
Carnegie Mellon Results 1 – Zimmerman et al. 2018



Sensor array in Pittsburgh using Real-time Affordable Multi-Pollutant (RAMP) sensor package

Zimmerman, N. et al. Presto, A. A., Kumar, S. P. N., Gu, J., Hauryliuk, A., Robinson, E. S., Robinson, A. L., Subramanian, R. A machine learning calibration model using random forests to improve sensor performance for lower-cost air quality monitoring, Atmospheric Measurement Techniques, 11, 291-313, DOI:10.5194/amt-11-291-2018. January 2018. https://www.atmos-meas-tech.net/11/291/2018/

Carnegie Mellon Results 2 – Zimmerman et al. 2018



Zimmerman, N. et al. Presto, A. A., Kumar, S. P. N., Gu, J., Hauryliuk, A., Robinson, E. S., Robinson, A. L., Subramanian, R. A machine learning calibration model using random forests to improve sensor performance for lower-cost air quality monitoring, Atmospheric Measurement Techniques, 11, 291-313, DOI:10.5194/amt-11-291-2018. January 2018. https://www.atmos-meas-tech.net/11/291/2018/

Courtesy of R. Subramanian

Next Steps – Slide 1 of 2

Research focus for the next year includes:

- **Carnegie Mellon University** – Continue to test and deploy RAMP sensor packages with Met-One neighborhood PM and PurpleAir PM sensors in environmental justice communities around Pittsburgh and expand the RAMP network; Improve RAMP website and study how communities use the data; comparisons between RAMP data and exposure/air quality models including land use regression (LUR) and chemical transport models.

- **Kansas State University/University of Memphis –** Work with communities in Chicago to deploy network of sensors identified in Year 1 of the project.

- **Massachusetts Institute of Technology –** Characterization of low-cost sensors based on data and laboratory studies; design, construction and testing of sensor nodes for full network deployment; design of project website, to provide community with real-time air quality data; engagement with local educators.

Next Steps – Slide 2 of 2

- **Research Triangle Institute –** In collaboration with the GES community, deploy the ambient air monitoring sensor network designed and tested in Year 1. Evaluate effectiveness of knowledge translation approaches (i.e., data type, data sharing modality, decision coaching for action steps design to reduce air pollution exposures) through personal monitoring. A Citizen Science research framework document will be developed using experience from this project.

- **South Coast Air Quality Management District –** Work with STI, UCLA, and community organizations to incorporate sensor-specific information into training videos, a guidebook and other educational materials. The updated guidebook will be used and evaluated during community workshops, and UCLA plans to test the project documentation for clarity and impact. Sensor deployment is beginning in participating communities.

- **University of Washington –** Continue to engage with the Project Advisory Committee and to work with undergraduate and high school EnvironMentors students to measure ambient air pollution levels from wood smoke in the Yakima Valley using low-cost monitors throughout the community. Revise the educational curriculum to include short PowerPoint presentations followed by an activity such as a data/graphing exercise and/or a discussion or debate.

EPA

For More Information

- To learn more about the Air Pollution Monitoring for Communities research projects, visit: https://www.epa.gov/air-research/air-pollution-monitoring-communities-grants
- The grantees are expected to attend the Air Sensors International Conference at the Oakland, California Convention Center, September 12th-14th, 2018.

ASIC Air Sensors International Conference

https://asic.aqrc.ucdavis.edu/

Program Area Summary

- **ORD and its partners have a diverse and well developed research plan to investigate and to the fullest extent possible, integrate emerging air quality technologies into its base research program**
- **ORD is recognized by external parties as one of the world-wide leaders in the discovery and evaluation of emerging technologies. EPA shares research findings through peer review literature and public venues such as the Air Sensor Toolbox website**
- **The value of new technologies to meet a wide range of stakeholder need (including EPA's) is an area of high interest. How "good" do they have to be to provide meaningful data? The Performance Target workshop discussions are attempting to stimulate progress in this area**
- **The call for emerging technologies to meet future air quality monitoring needs has arrived. ORD will continue to seek to provide definition on the value of such technologies and integrate these successfully in real-world environments**

Resources and Contact Information

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

Ron Williams
Williams.Ronald@epa.gov

Vasu Kilaru
Kilaru.Vasu@epa.gov