Sensor Technologies: Lessons Learned

U.S. EPA's Emerging Technologies Research Program

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May 1, 2017

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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

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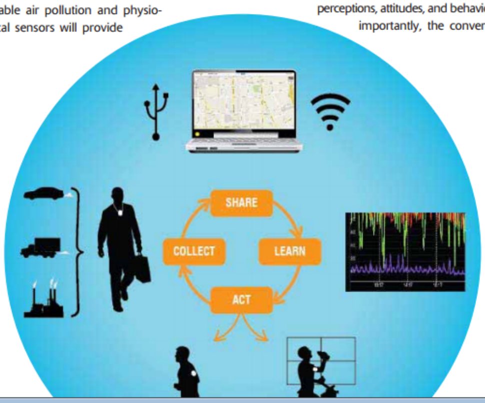
A summary overview of discussions during EPA's Apps and Sensors for Air Pollution (ASAP) Workshop, held March 2012 in Research Triangle Park, NC, where the current state of the science, data management. and community efforts involving apps and sensors were the focus. This article highlights some of the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

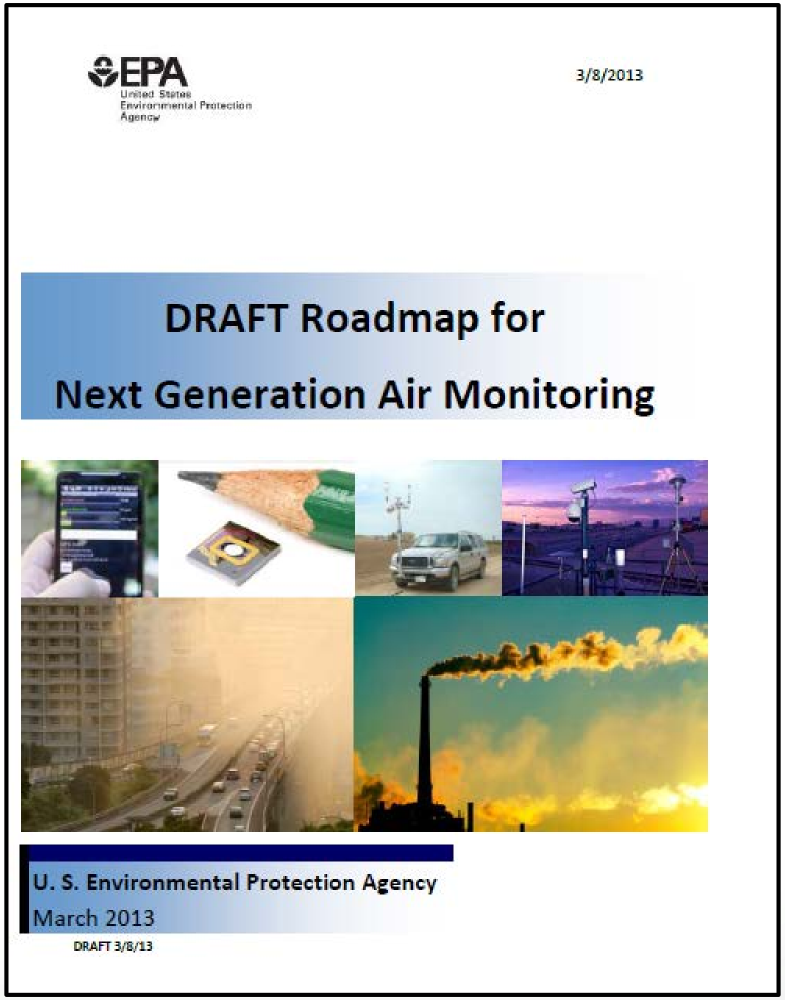
In order to take relevant measurements, it is evident that communities need information on the appropriate accuracy, precision, and range of operating conditions (e.g., concentration ranges, environmental conditions, etc.) for their devices. Thus, air quality monitoring guidelines for low-cost sensors 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.

A Call for Research

- **Determine the state of the science (Discovery)**
- **Where could EPA make greatest immediate impact (Evaluation)**
- **Integrate into research portfolio (Application)**
- **NAAQS pollutants would be initial focus (PM, NO_2, O_3, SO_2, CO)**



EPA

Emerging Technologies Research Agenda

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

Disclaimer

Mention of trade names or commercial products does not constitute endorsement or recommendation for use and are provided here solely for informational purposes

Discovery-Low Cost (<$2500) Sensors

SENSARIS

AIR CASTING

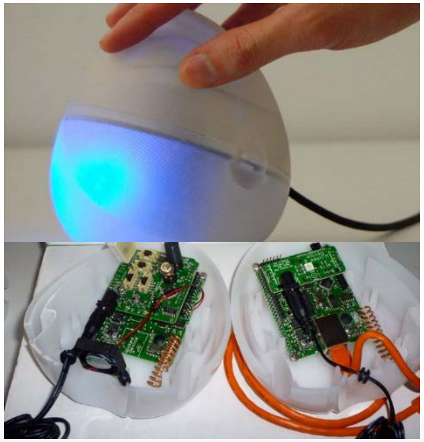
AirCasting App

AirCasting Air Monitor

CAIRCLIP

AEROQUAL

AQ EGG



NODE

Discovery-Mid-tier Cost (>$2500) Sensors

Thermo pDR

DUSTTRAK DRX

AQ MESH

Perkin Elmer ELM

2B OEM-106 Ozone

tVOC- PID

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 Discovery and Resources

Air Sensor
Measure · Learn · Share
Citizen Science Toolbox

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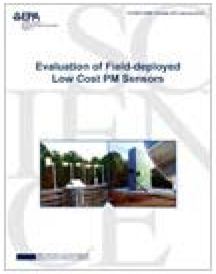
Online Resources Available at:
www2.epa.gov/air-research/air-sensor-toolbox-citizen-scientists

Air Sensor Guidebook

CSAM Operating Procedures

Mobile Sensors & Applications for Air Pollutants

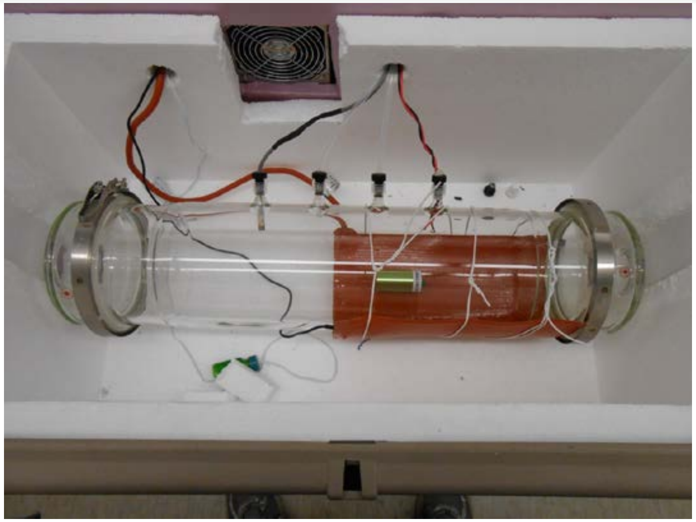
Citizen Science Air Monitor (CSAM): Quality Assurance Guidelines



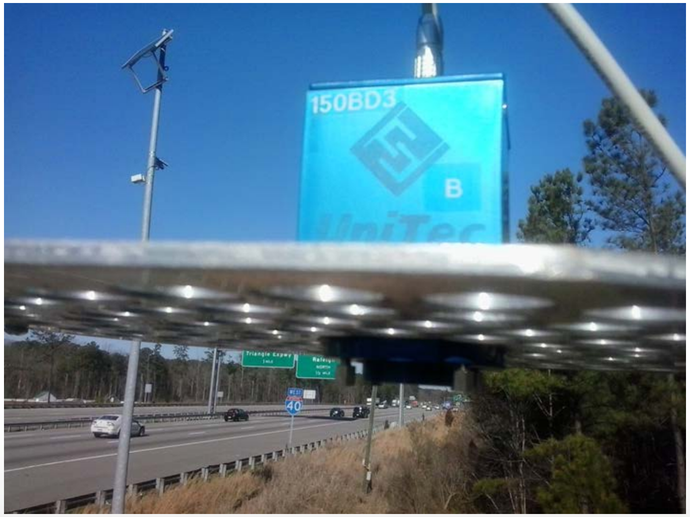
Evaluation of Field-deployed Low Cost PM Sensors

Sensor Evaluation-Approach

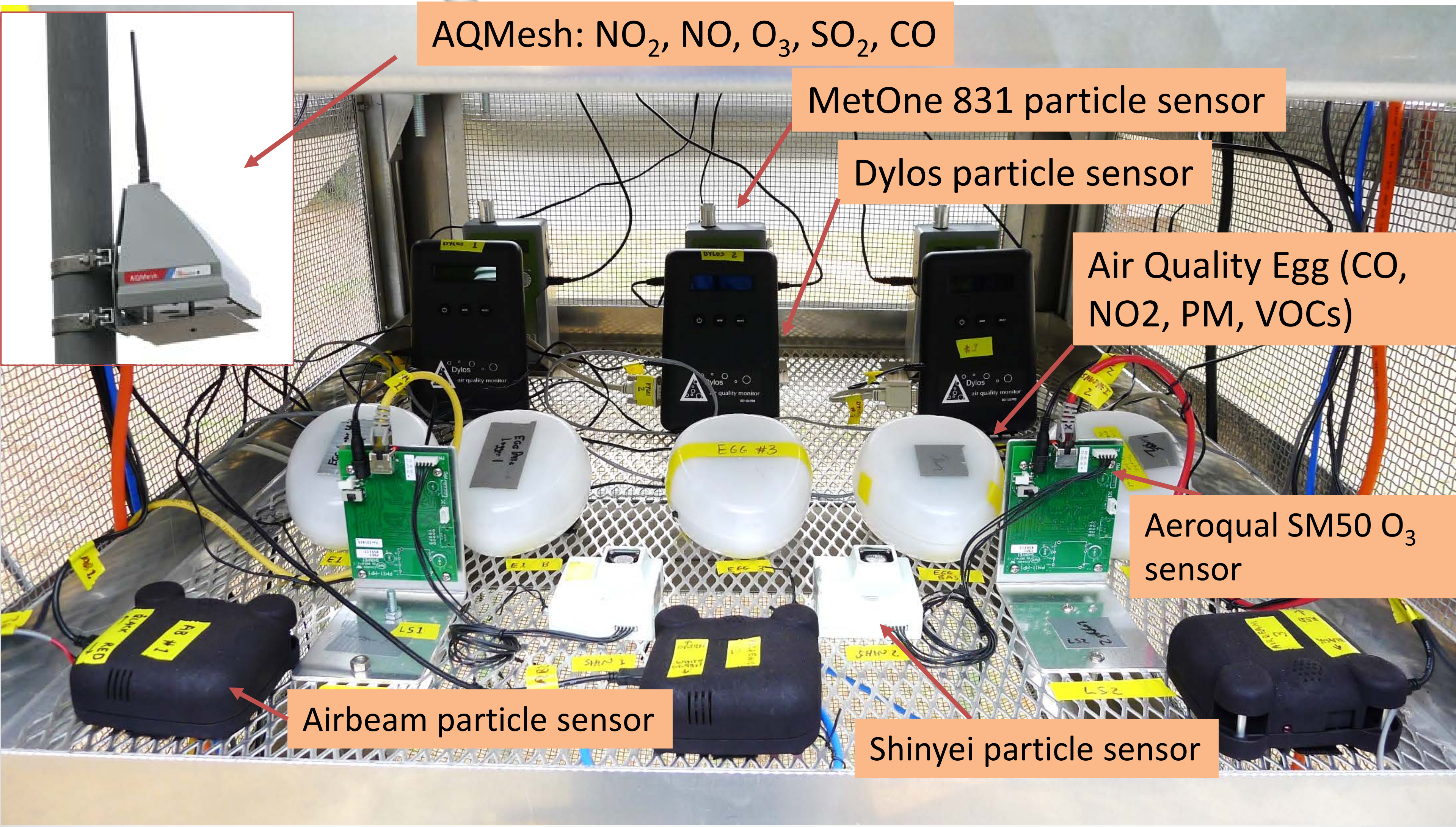
Direct chamber testing of select gas phase low cost sensors



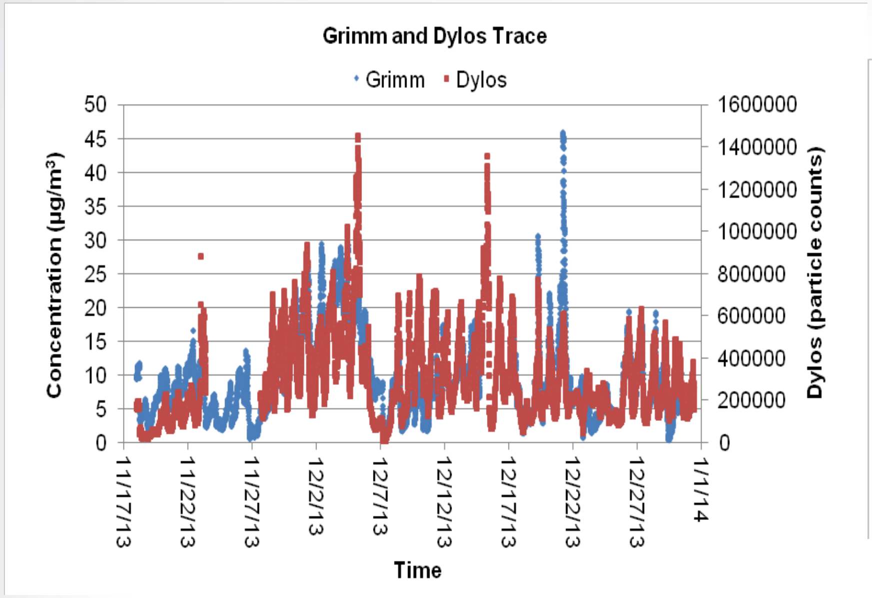
Collocation of select gas and particulate matter sensors with reference monitors

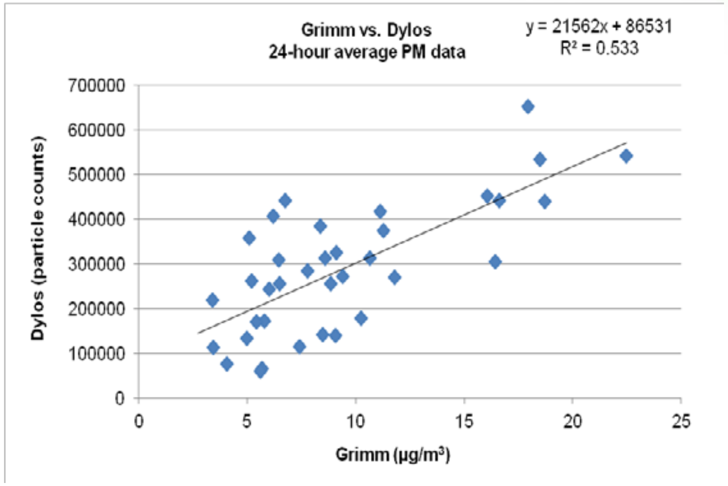


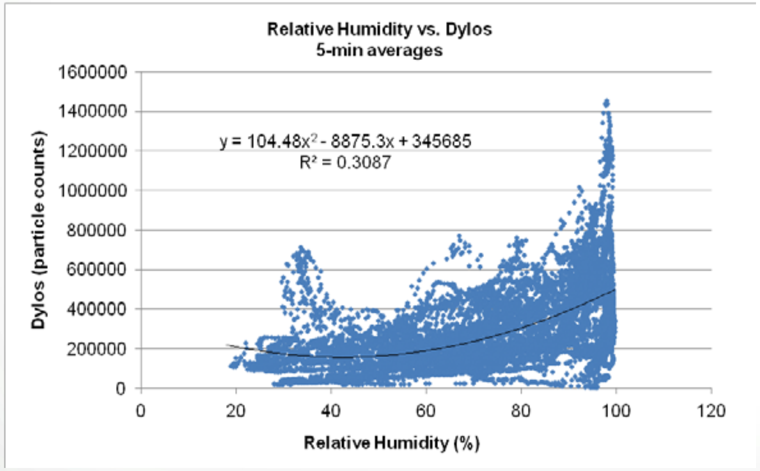
Direct Collocation Evaluation

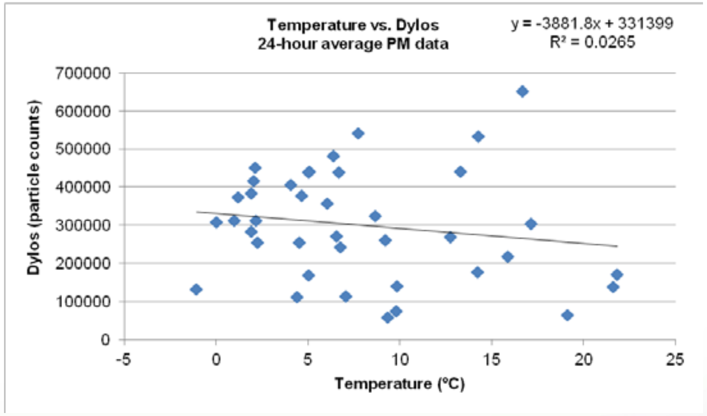


An Example of In-Depth PM Sensor Evaluation

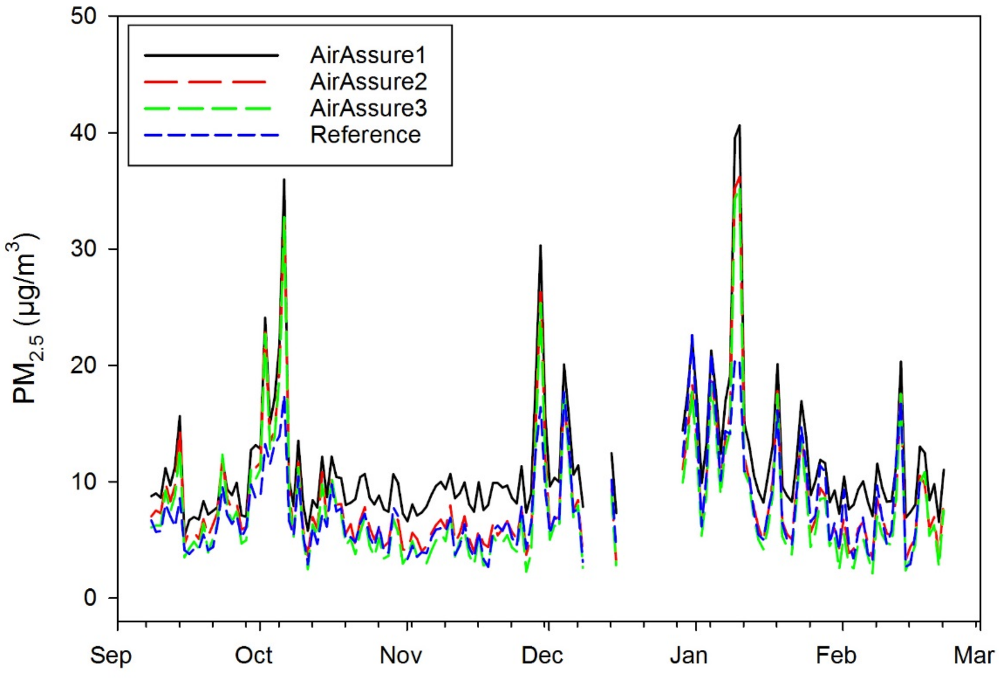


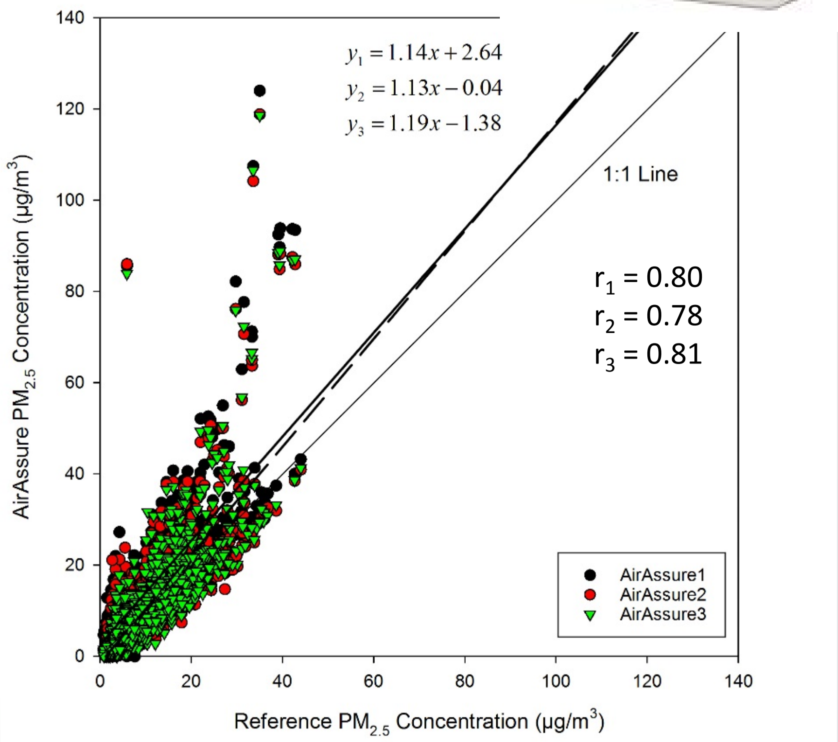






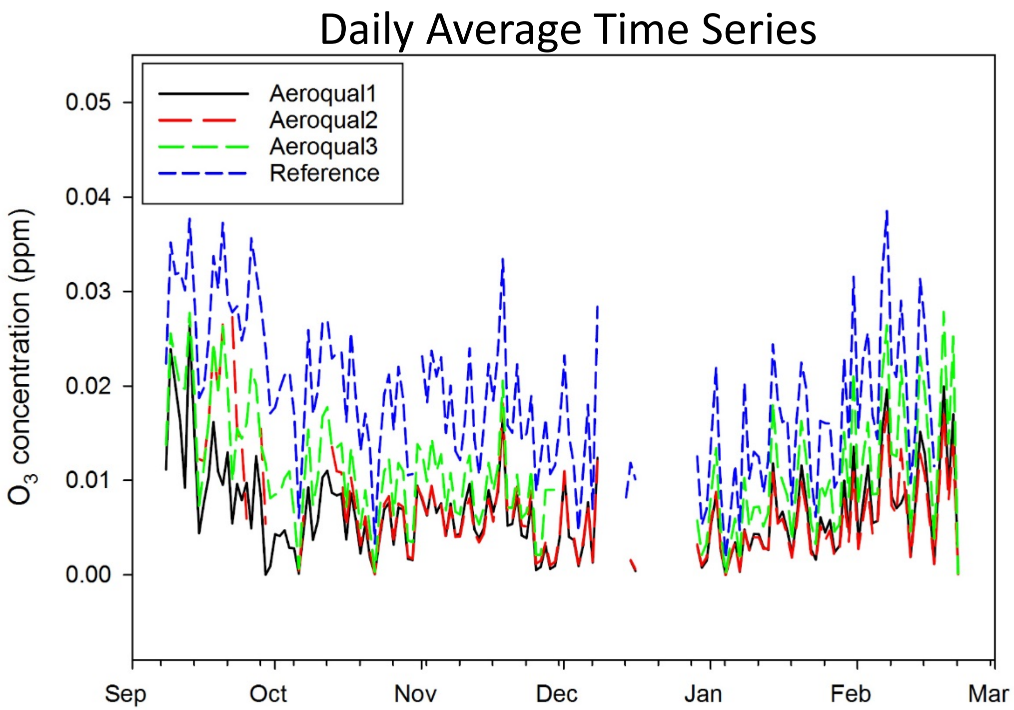
AirAssure – $PM_{2.5}$

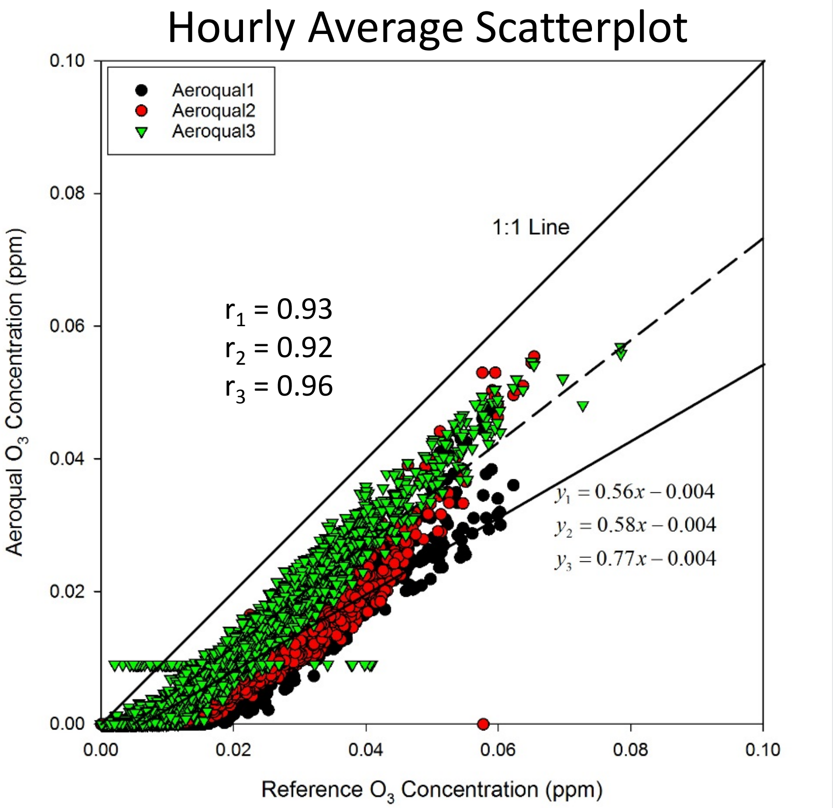




- Few over-responding events
- Strong agreement between units 2 and 3
- Strong correlation with monitor

Aeroqual – O_3





- Initial lab audit had 1:1 ratio
- Underreports regulatory monitor O_3
- Consistent across seasons
- Strong correlation to regulatory monitor

Hourly Average PM Correlations

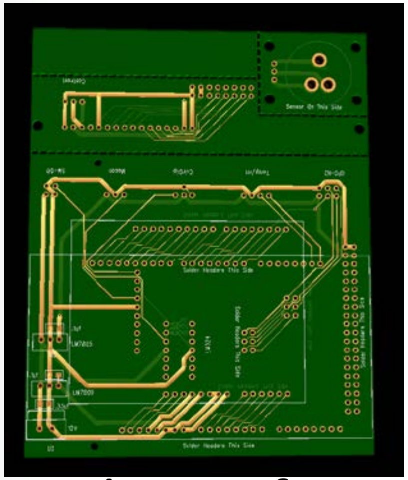
	AirAssure1	AirAssure2	AirAssure3	Airbeam1	Airbeam2	Airbeam3	DylosF1	DylosF2	DylosF3	OPCF1	OPCF2	OPCF3	Speck1	Speck2	Speck3	Shinyei1	Shinyei2	Shinyei3	TZOA1	TZOA2	TZOA3	Regulatory
AirAssure1	100																					
AirAssure2	98	100																				
AirAssure3	98	98	100																			
Airbeam1	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 mass concentration or particle number correlation within model types
- Correlations with regulatory monitors range from weak to very strong
- Hourly average values had strongest correlations

Sensor Application

- Developing first generation sensor pods



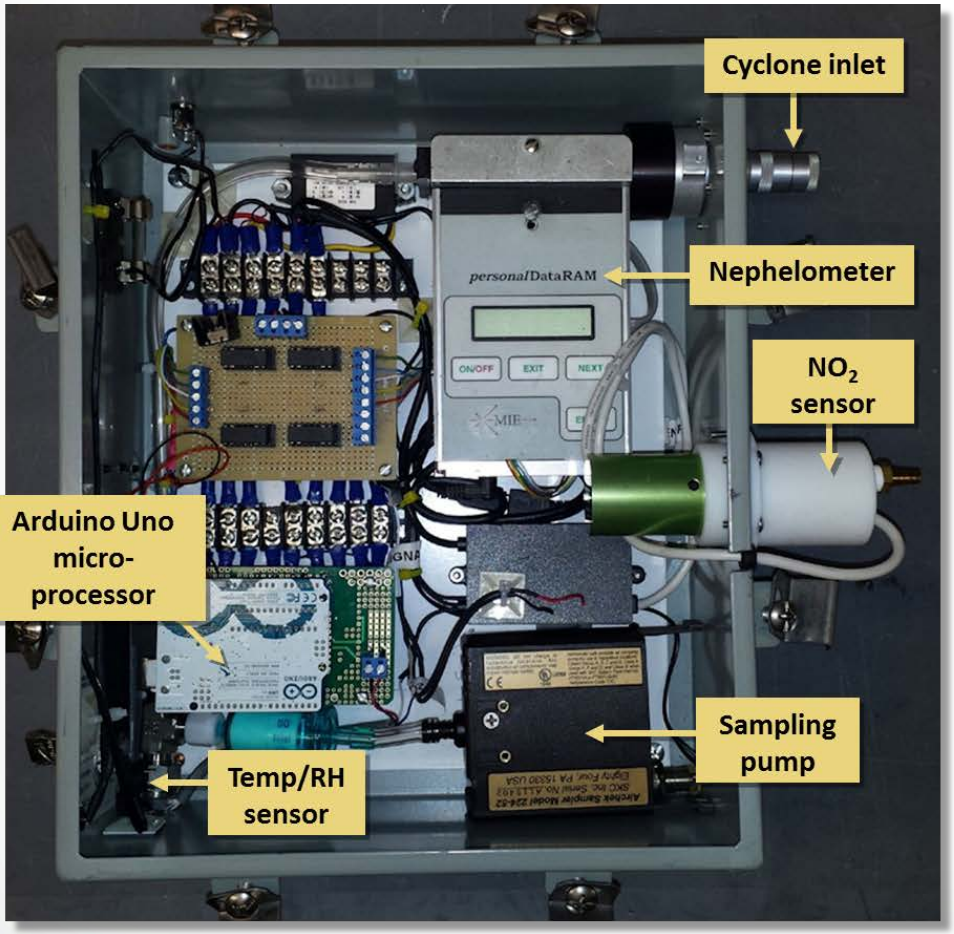
pod-specific control boards

Solar and/or land powered pods

AIRMAPPER

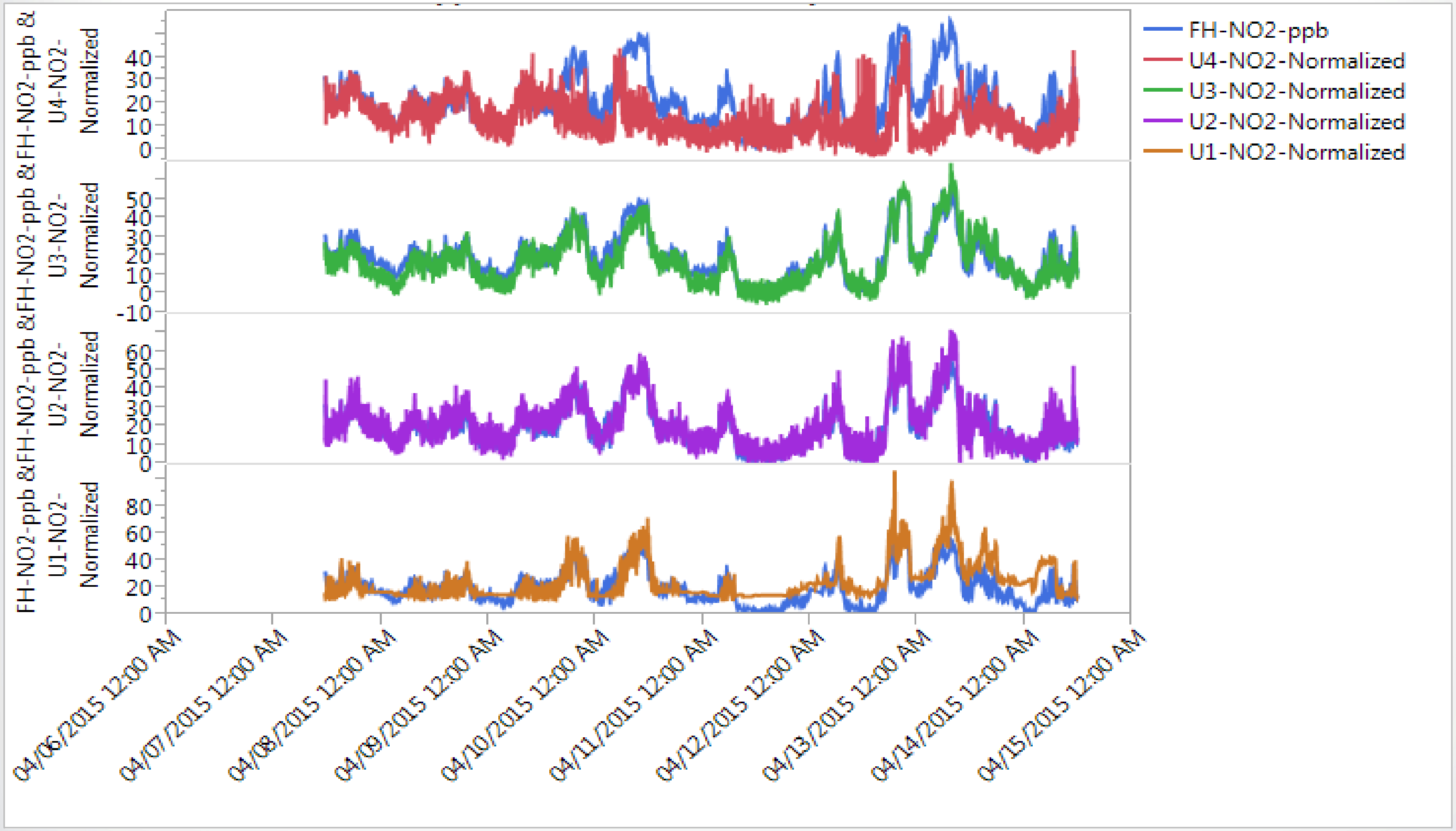
- Developing data processing code associated with low cost microprocessors (e.g., Arduino, Teensy, Raspberry Pi)
- Integrating sensors into a wide variety of EPA field research activities

Application– the CSAM



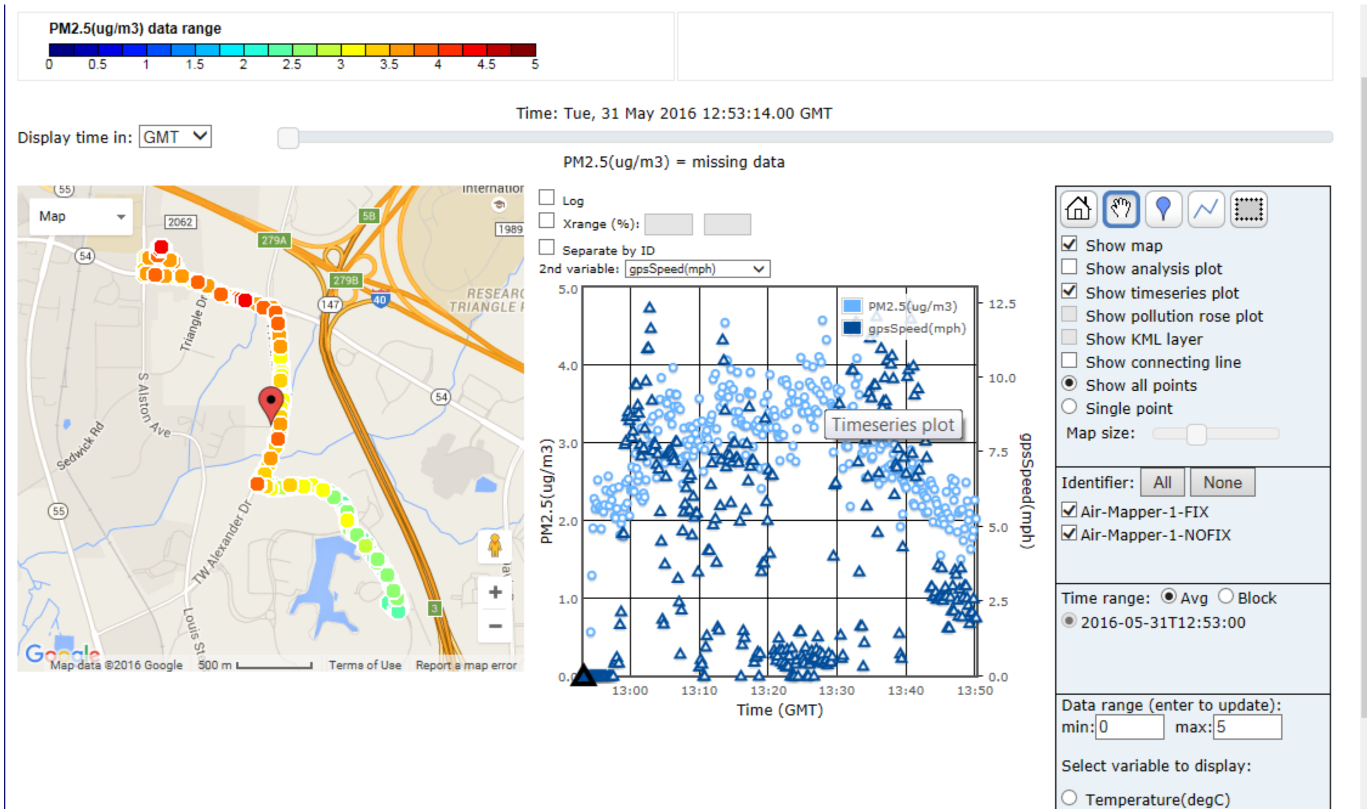
Measurement	Reporting Unit
NO_2 concentration	Parts per billion (ppb)
PM concentration	Micrograms per cubic meter (µg/m^3)
Temperature	Degrees Celsius (°C)
Relative humidity (RH)	Percent (%) at °C

Sensor Response Normalization (NO_2) Cairclip vs Federal Equivalent Monitor



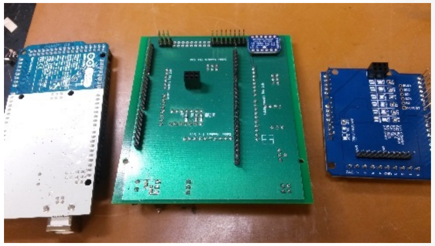
Application- AIRMAPPER with RETIGO

RETIGO- Data visualization and data sharing tool



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

General Research Conclusions



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 Conclusions

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

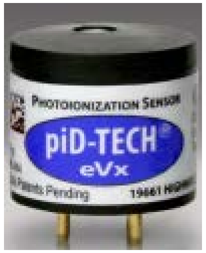
- Component (~$50 to $300) to Complete Pod systems ($1500-$10K) exist
- O_3 sensors (~ $50-$1500) have shown excellent reference agreement ($R^2 > 0.9$); Detection limit = ~5 ppb
- NO_2 sensors (~$50-$1500) co-responsive with O_3 and must be resolved ($R^2 > 0.8$); Detection limit = ~5 ppb
- SO_2 sensors (~$50-$1500) have poorest limits of detection being reported (~50 ppb). Little improvement observed during 20012 to present
- CO sensors (~$100-$2500) have difficulty with <5 ppm measurements and temperature changes

General Research Conclusions

Selection of Meteorological Sensors

- Components (~$30 to $1500)
- Ultrasonic, vane and cup designs are options
- RH and temp are <u>must have</u> 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

The Take Home Message

- We have examined and continue to examine sensors as they become available
- We are integrating these technologies into a variety of research projects
- Investigating lower cost devices (< $2500)
- A wide range in capabilities are being observed. Cost is not necessarily the driver in how well any given device might function
- Fewer options available for air toxics. VOCs, ammonia, hydrogen sulfide, methane, etc limited in the low cost category
- New data visualization tools like RETIGO are now available for use
- Demand to understand this technology sector is only increasing in intensity
- Application requirements determine the data quality and sensor options for a given research need

Sensor Related Resources

Air Sensor
Measure · Learn · Share
Citizen Science Toolbox

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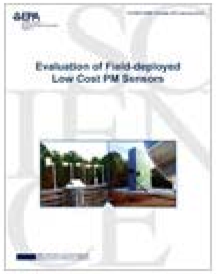

Evaluation of Field-deployed Low Cost PM Sensors