



Next Generation Air Monitoring (NGAM) - Technology Evaluation and Application Research

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Project Leads

US EPA's Air Climate & Energy (ACE)

Emerging Technologies Research Program

**Instituto Nacional De Ecología Y Cambio
Climático (INECC)**

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Democratization in monitoring is being enabled by.....

1. Smartphones with embedded sensors and communications (gps, wifi...)
2. The Internet of Things (IoT) & Cloud Computing
3. Crowd Sourcing and Civic/participatory Science
4. DIY and microelectronics revolution (Arduino, Raspberry Pi...)
5. Desire for personalized & customized information

So where is all this headed?.....

1. Weather Underground analogy and digital mutualism (waze app...)
2. State-of-the-Art data assimilation and integration (satellite, sensors, FRM)
3. Robotics, sensors, Cognitive Computing (UAVs)
4. Mobile Health -> Precision Medicine and Epidemiology
5. Exposomics



Emerging Technologies Research Agenda

1. Conducted literature survey on the state of sensor technologies
2. Screened market surveys for commercially-available air sensors
3. Convened workshops to enable dialog among regulators, researchers, device makers, and civic interests
4. Established a Sensor Roadmap by focusing on high priority issues (NAAQS, Air Toxics, Civic participation)
5. Performing technology evaluations on low cost sensors (lab + in-situ)
6. Developing in-house sensor systems (Village Green, CSAM, Spod)
7. Disseminating knowledge to a wide range of stakeholders (sensor developers, users) via user guides and webinars
8. Working with sensor developers to speed up development, improve data quality, establish data standards, and ensure open data access
9. Establishing highly integrated research efforts across EPA and internationally
10. Applying knowledge gained in hands-on sensor deployment activities



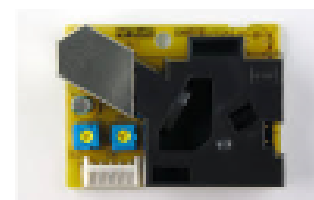
Pollutants of Interest

Air Pollutant of Interest	Useful Detection Limits	Range to Expect	Level
Ozone (O ₃)	10 ppb	0-150 ppb	70 ppb (8 hr)
Carbon monoxide (CO)	0.1 ppm	0-0.3 ppm	9 ppm (8 hr) 35 ppm (1 hr)
Sulfur dioxide_(SO ₂)	10 ppb	0-100 ppb	75 ppb (1 hr) 0.5 ppm (3 hr)
Nitrogen dioxide_(NO ₂)	10 ppb	0-50 ppb	100 ppb (1 hr) 53 ppb (1 yr)
Carbon dioxide (CO ₂)	100 ppm	350-600 ppm	None
Volatile organic compounds (VOCs)	1 µg/m ³	5-100 µg/m ³ (total VOCs)	None
Benzene (an example of a VOC and air toxic)	0.01 – 10 µg/m ³	0-3 µg/m ³	None
Fine particulate matter (PM _{2.5})	5 µg/m ³ (24-hr)	0-40 µg/m ³ (24-hr)	35 µg/m ³ (24 hr) 12 µg/m ³ (1 yr)
Particulate matter (PM ₁₀)	10 µg/m ³ (24-hr)	0-100 µg/m ³ (24-hr)	150 µg/m ³ (24 hr)
Black carbon (BC)	0.05 µg/m ³	0-15 µg/m ³	None

Metal Oxide (MOS)/Electrochemical and Light Scattering Sensors



- The most widely available of all gas sensor types
- Inexpensive (\$15-\$300)
- Available in a wide array of pollutants
- Often not specific to any one pollutant
- Co-factors often influence their output
- Response relational to some given parameter



- Light scattering sensors dominate market
- Cost varies (\$50-6000)
- Sensitive to RH and stray light
- Size definition varies widely
- Unit output definition varies widely
- Aerosol composition influences response
- Not true mass measurement

Photo credit: <http://www.alpha-sense.com/>



Example – PM Sensors

DYLOS



SPECK



MET ONE



SHINYEI



AIRBEAM



TZOA



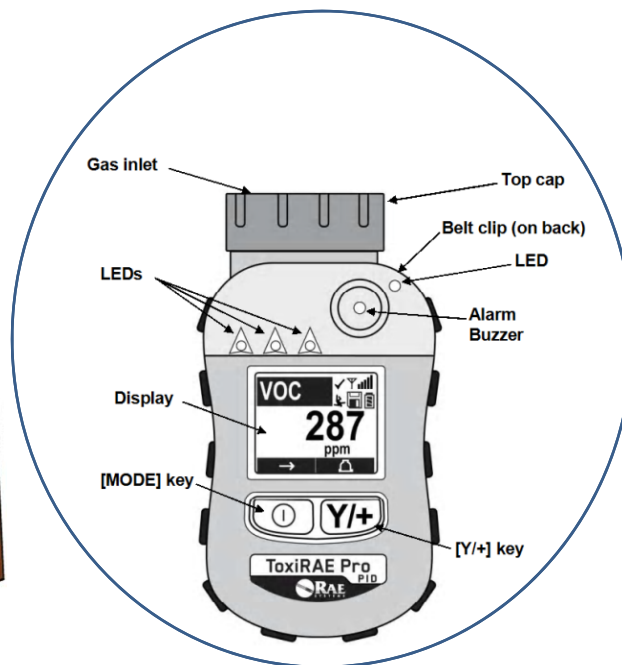


Example – VOC Sensors

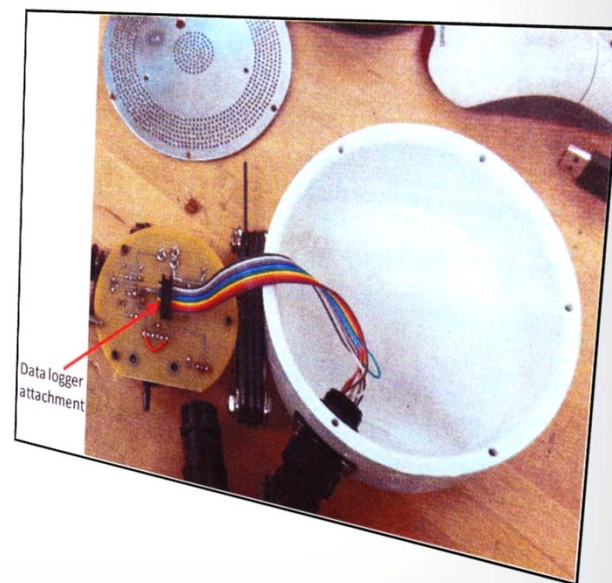
UniTech



ToxiRae



EPA VOC





Example – Gas Sensors

SENSARIS



AIR CASTING



AirCasting App



AirCasting Air Monitor

CAIRCLIP



AEROQUAL



AQ EGG



NODE





Example – Multipollutant Stations



ELM



HAZ-SCANNER



AQ MESH



Recent Activities

2012

ASAP workshop

Sensors Evaluation
and Collaboration

2013

Regions workshop

Short-term sensor field tests

Designing/building autonomous
systems: Village Green Project

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

2014

Air sensors workshop

Short-term sensor field tests

2015

Air Sensors Toolbox

CSAM-Citizen Science

Designing/building autonomous
systems: Village Green Project II

Long-term testing: Regional Methods Project -CAIRSENSE

Sensor network
intelligent emissions
locator tool (SENTINEL)

Data visualization: RETIGO

Community training



Ongoing/Planned Activities

AWMA/NACAA/APCA/Tribal Nations/others

Long-term testing: Regional Methods Project -CAIRSENSE

Short-term sensor field tests

Design Citizen Science applications

Designing/building autonomous systems: Village Green Project v. II

Data visualization: RETIGO V2

Sensor network intelligent emissions locator tool (SENTINEL) and advanced S-POD development

Data sharing with stakeholders

Summarize state of the science

New sensor evaluation initiative?

Field Citizen Science applications

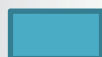
Designing/building autonomous systems: Village Green Project v. III

SENTINEL and S-POD advancements

Data visualization: RETIGO V2

2016

2017



Data sharing



Performance testing



Sensor system build



Sensor data tools

EPA's Recent Community Air Monitoring Training Event

- Goals:
 - To share tools, best practices, and resources from EPA's Air Sensor Toolbox for Citizen Scientists
 - To educate interested groups and individuals on how to conduct successful air monitoring projects
- 30 in-person attendees, 800+ via webinar
- Training videos now available on Air Sensor Toolbox website
- Ongoing follow-up with Regions/State/Tribal interests





Sensor Related Resources



Contacts: **Ron Williams** 919-541-2957 williams.ron@epa.gov
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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



Critical Peer Reviewed Articles Defining Emerging Sensor Technology


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

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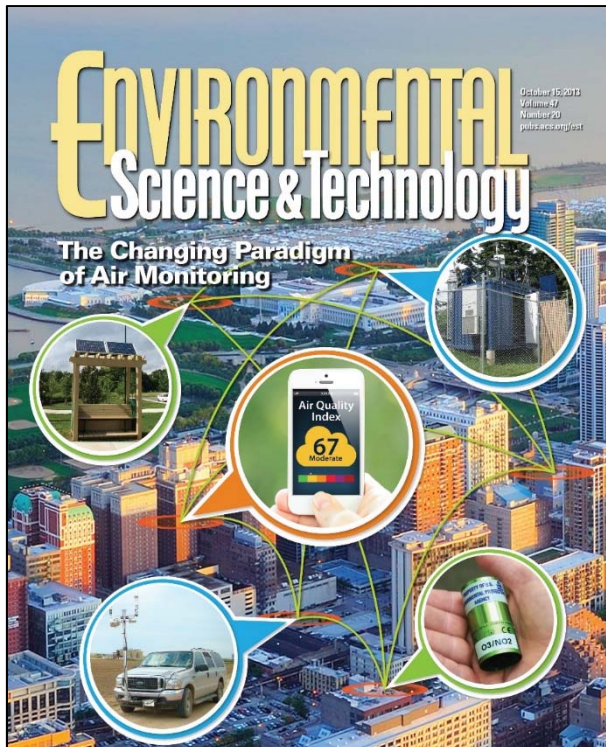


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The Changing Paradigm of Air Monitoring



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JANUARY 2014

Also in this issue:
CalEnviroScreen: A Pathway to Address
Environmental Justice Issues in California
PM File: Storyboarding Builds
Persuasive Presentations

Air Quality Sensors, Part 1

Findings from the 2013 EPA Air Sensors Workshop,
including emerging sensor technologies (e.g. Smartphone
Apps), data challenges and solutions, and sensor
calibration options



Select Quality Assurance Parameters Involving Continuous Monitoring

- **Bias**-is it routinely high or low with respect to the true value
- **Precision**- how repeatable is the measurement
- **Calibration**- does it respond in a systematic fashion as conc changes
- **Detection limit** -how low and high will it measure successfully
- **Response time** -how fast does the response vary with conc change
- **Linearity of sensor response** -what is the linear or multilinear range
- **Measurement duration** -how much data do you need to collect
- **Measurement frequency** -how many collection periods are needed
- **Data aggregation** -value in aggregating data (1 sec, 1 min, 1 hr, etc)
- **Selectivity/specificity** -does it respond to anything else
- **Interferences** -how does heat, cold, effect response
- **Sensor poisoning and expiration** -how long will the sensor be useful
- **Concentration range** -will the device cover expected highs and lows
- **Drift** -how stable is the response
- **Accuracy of timestamp** - what response output relates to the event
- **Climate susceptibility** - does RH, temp, direct sun, etc impact data
- **Data completeness** -what is the uptime of the sensor
- **Response to loss of power** - what happens when it shuts down

Direct Collocation with FEMs



Ad-Hoc Testing

AQMesh: NO₂, NO, O₃, SO₂, CO

MetOne 831 particle sensor

Dylos particle sensor

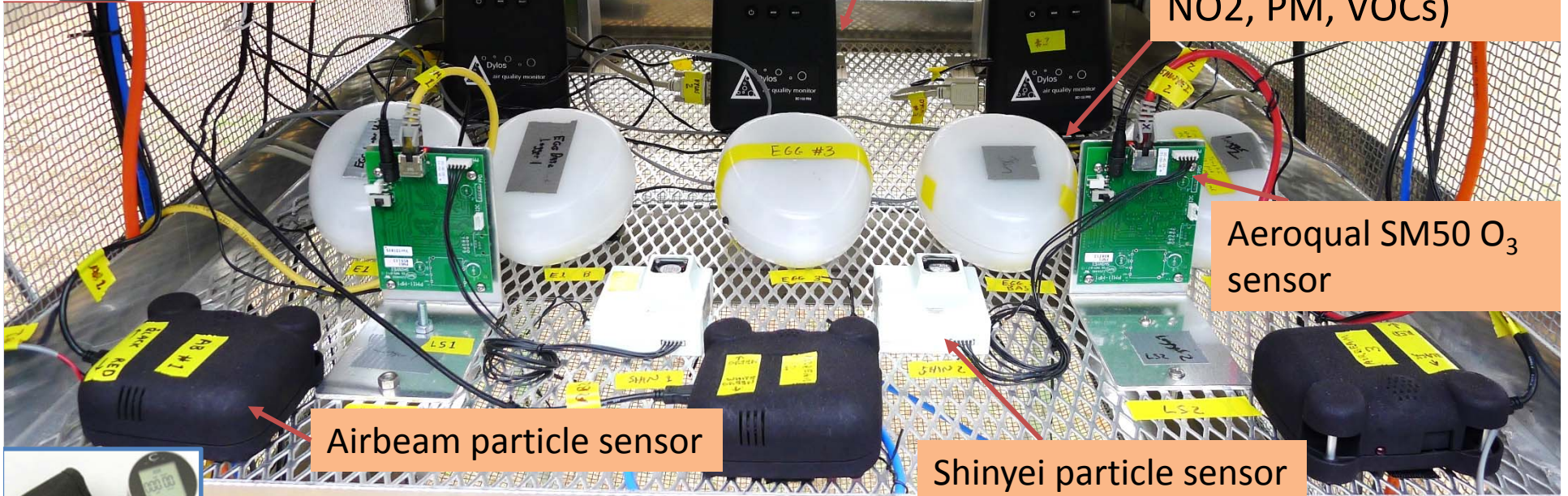
Air Quality Egg (CO, NO₂, PM, VOCs)

Aeroqual SM50 O₃ sensor

Airbeam particle sensor

Shinyei particle sensor

Not shown: Cairpol NO₂/O₃ sensor

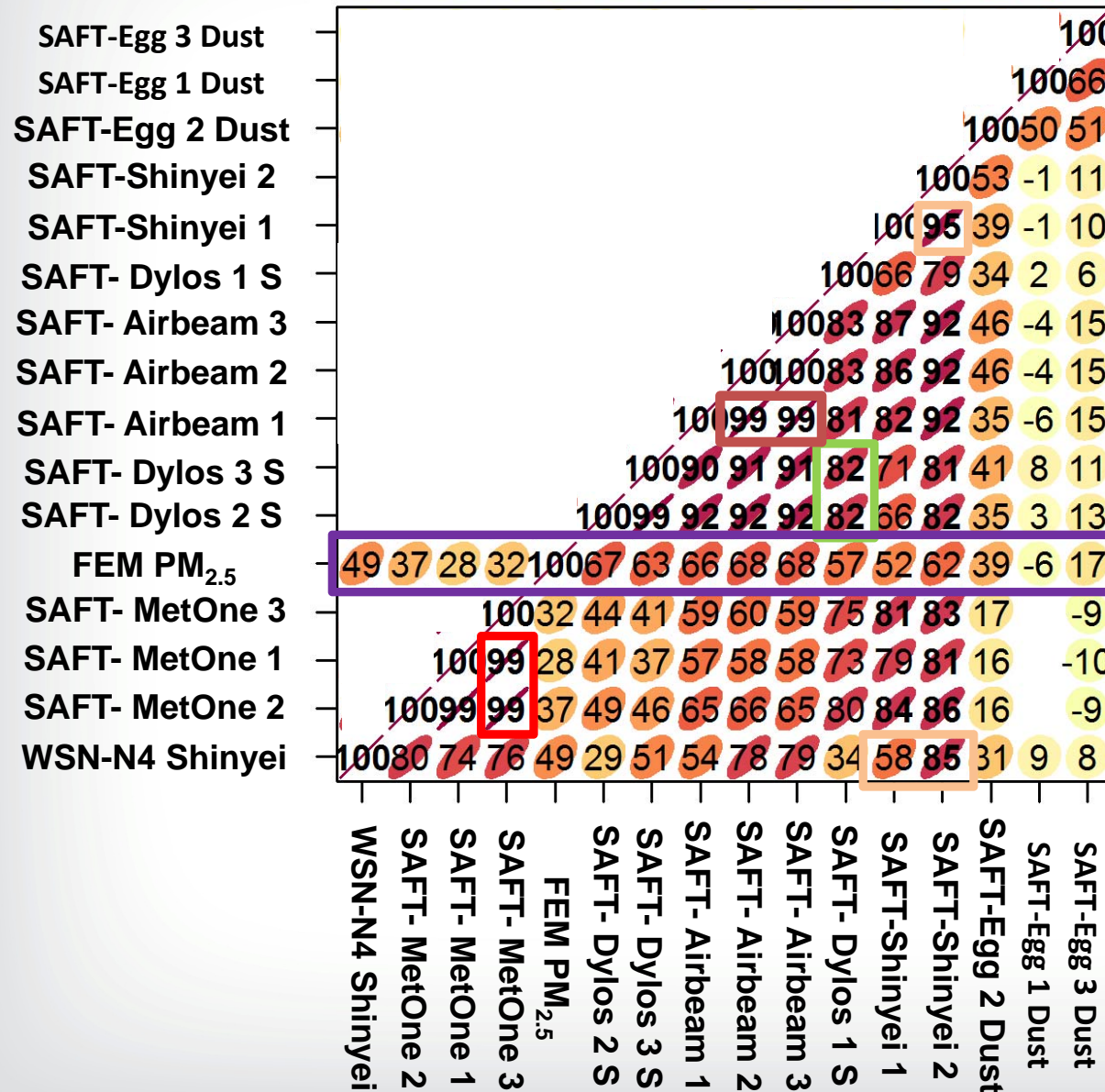


Atlanta and Denver- Climate Extremes



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

Correlation matrix (Pearson correlation) of 12-hr average PM between sensors and co-located FEM



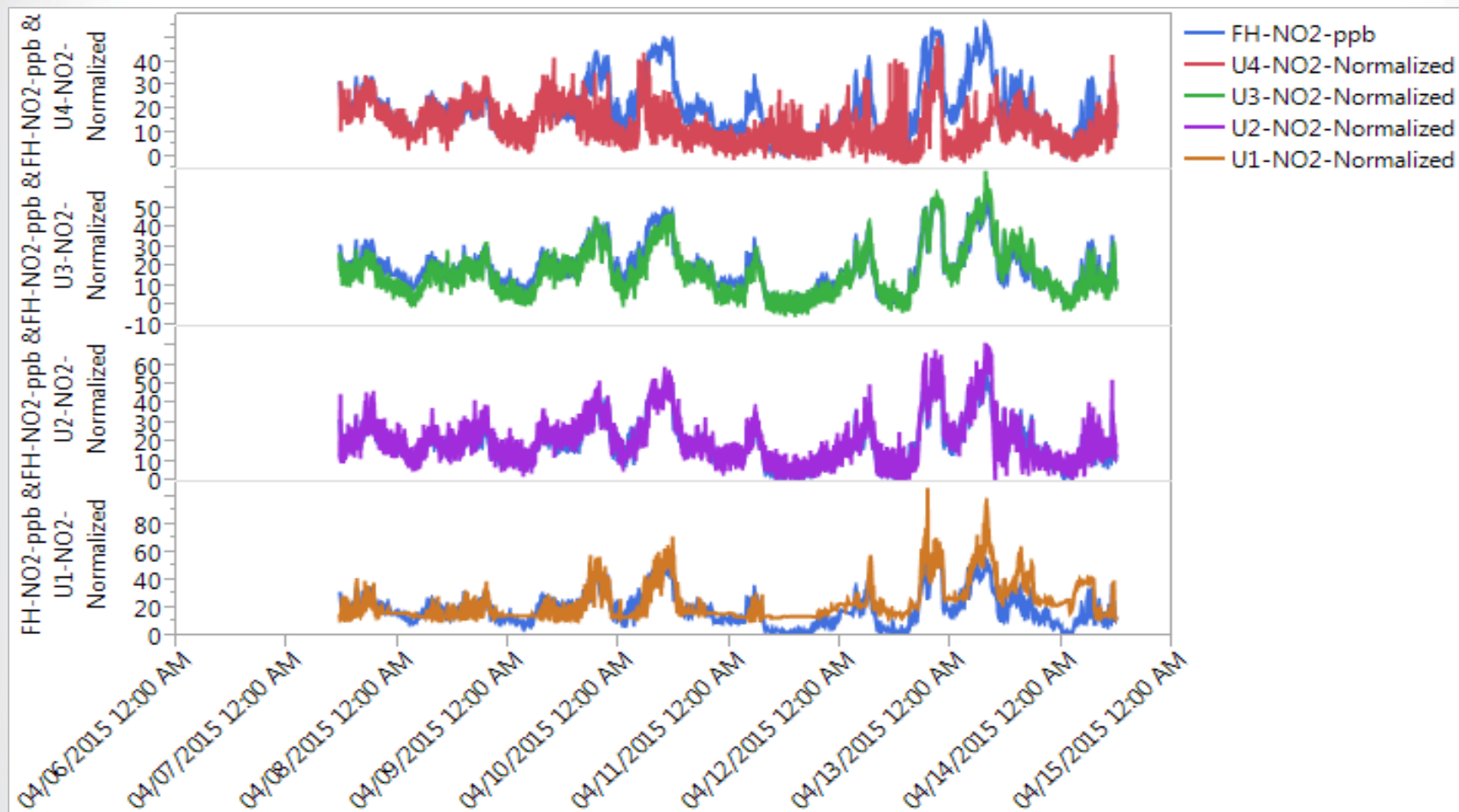
Moderate to high correlation between most identical units



Variable correlation with reference ($r = -0.06$ to 0.68)



Sensor Response Normalization (NO₂) CSAM vs FEM





ORD-Region example research projects using sensors

Goal: Support community group in using low-cost sensors to explore their air quality



- Designed for use by citizens/students
- Local (on-board) data storage
- Designed for ease of use by non-professionals
- Lessons learned from ORD evaluations integrated into design function (e.g., technology selected /data visualization tools employed)



ORD-Region research projects using sensors (FY15-16)

Project / Year	Regional Partner(s)	Measurements	Location
CAIRSENSE (ongoing)	Region 1 Region 4 Region 5 Region 7 Region 8	PM, ozone, nitrogen dioxide – four sensor nodes	Atlanta, GA
CSAM (Being summarized)	Region 2	PM, NO ₂ , temperature, humidity – portable stations	Ironbound community, NJ
<i>CitySpace (Under development)</i>	<i>Region 4 Region 6 Region 7</i>	<i>PM – up to 20 stationary nodes</i>	<i>Memphis, TN</i>
<i>AirMapper (Under development)</i>	<i>Region 5 Region 10</i>	<i>PM, noise, temperature, humidity – portable units</i>	<i>Chicago, IL Portland, OR</i>
<i>Puerto Rico EJ (Under development)</i>	<i>Region 2</i>	<i>Tentative: PM, VOCs, NO₂ – portable units</i>	<i>Puerto Rico</i>



Possible Sensor Tiers

Tier	Application Area	Precision and Bias Error	Data Completeness*	Rationale (Tier I-IV)
I	Education and Information	<50%	≥ 50%	Measurement error is not as important as simply demonstrating that the pollutant exists in some wide range of concentration.
II	Hotspot Identification and Characterization	<30%	≥ 75%	Higher data quality is needed here to ensure that not only does the pollutant of interest exist in the local atmosphere, but also at a concentration that is close to its true value.
III	Supplemental Monitoring	<20%	≥ 80%	Supplemental monitoring might have value in potentially providing additional air quality data to complement existing monitors. To be useful in providing such complementary data, it must be of sufficient quality to ensure that the additional information is helping to “fill in” monitoring gaps rather than making the situation less understood.
IV	Personal Exposure	<30%	≥ 80%	Many factors can influence personal exposures to air pollutants. Precision and bias errors suggested here are representative of those reported in the scientific literature under a variety of circumstances. Error rates higher than these make it difficult to understand how, when, and why personal exposures have occurred.

Data Visualization Tools-RETIGO

REAL-TIME GEOSPATIAL DATA VIEWER (RETIGO)

AN EPA-DEVELOPED WEB-BASED TOOL FOR RESEARCHERS AND CITIZEN SCIENTISTS TO EXPLORE THEIR AIR MEASUREMENTS



Screenshot showing RETIGO in action, where data are displayed on a map and in one of the chart options.

- Free, on-line data visualization tool for spatially resolved air quality measurements
- Designed for plug and play data handling scenarios
- Provides time and spatial features of your dataset
- On-line tutorials provide step by step user instructions
- Available at <http://www.epa.gov/hesc/real-time-geospatial-data-viewer>



Village Green Project

- Prototype located in North Carolina, USA 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 $\leq 2.5 \mu\text{m}$)
- 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>





New Village Green Pilot Project

Partners: City of Philadelphia,
National Park Service



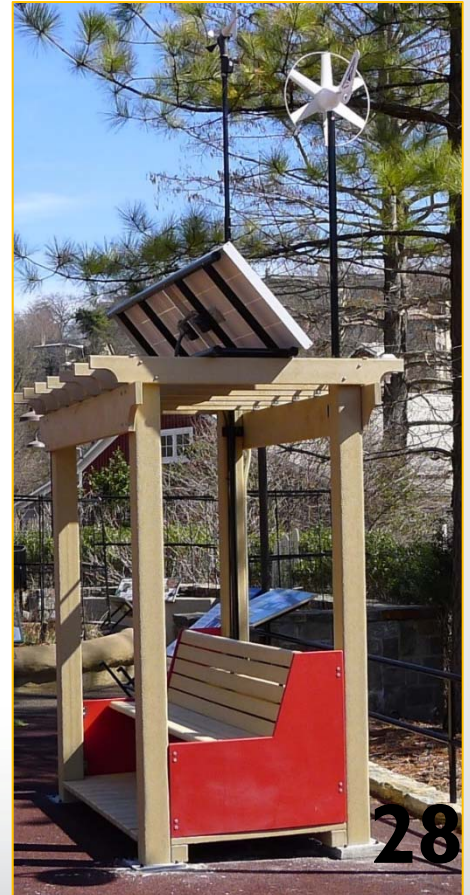
Partners: State of Oklahoma, Myriad
Botanical Gardens



Partners: State of
Kansas, Wyandotte
County, School
District



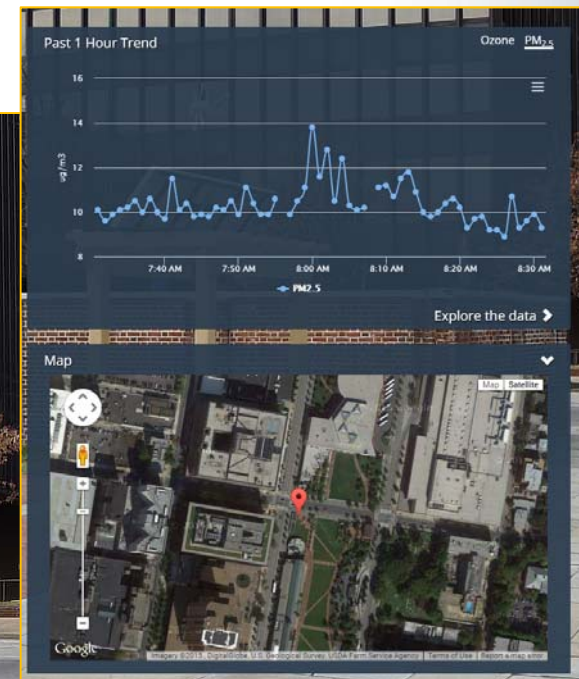
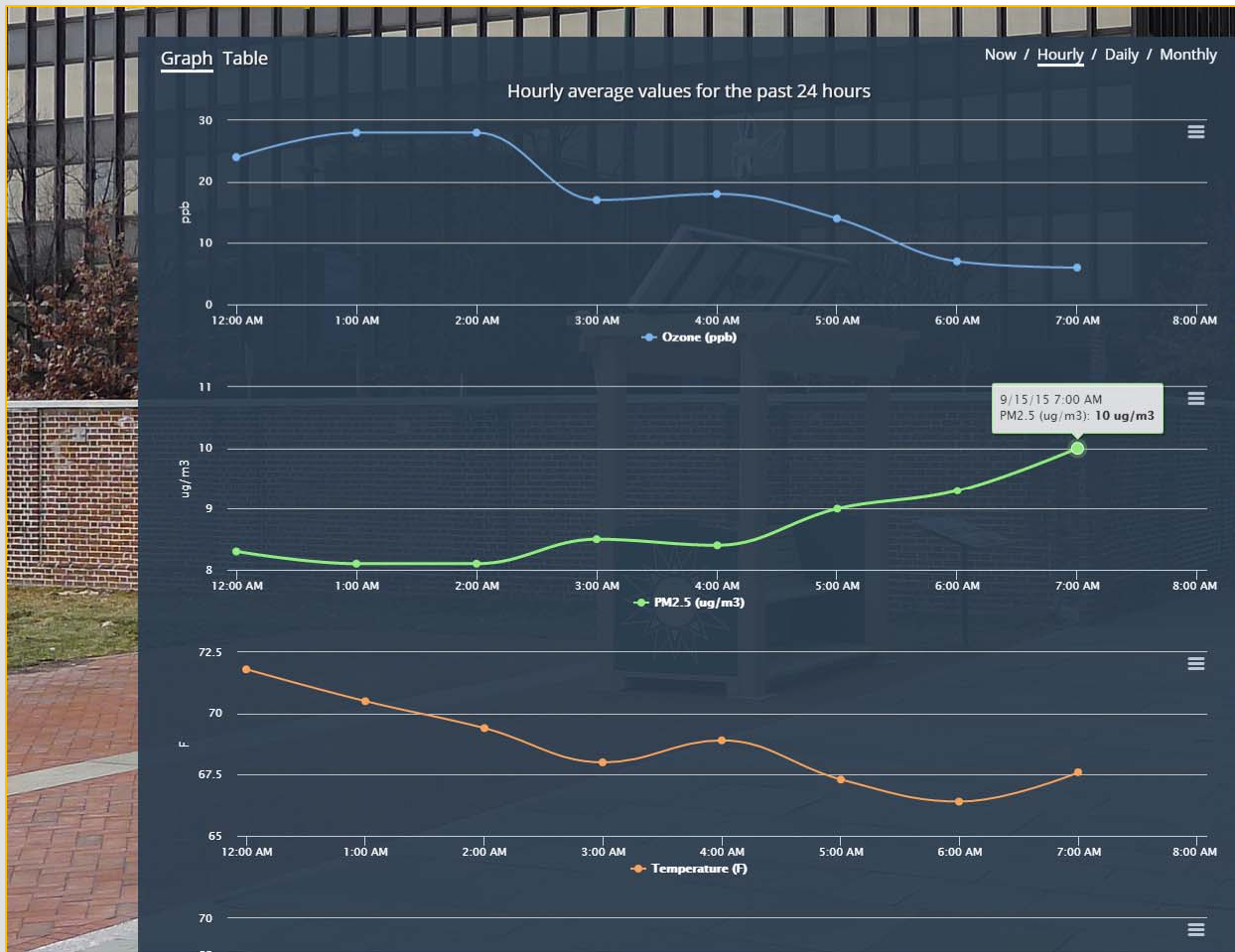
Partners: District
Department of the
Environment,
Smithsonian





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} ug/m ³	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	58.5	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	
9/14 7:00 PM	25	7.4	76.5	37.8	
9/14 6:00 PM	31	7.4	78.4	32.1	
9/14 5:00 PM	31	6.8	79.3	30.2	3.4

Mid-Tier VOC Research Efforts

- High demand by wide range of stakeholders for continuous VOC monitoring with lower operational costs
- EPA investigating low cost as well as mid-tier (\$5-10K) technologies to define the state of the science and how they might be applied

In-plant /
Work Truck

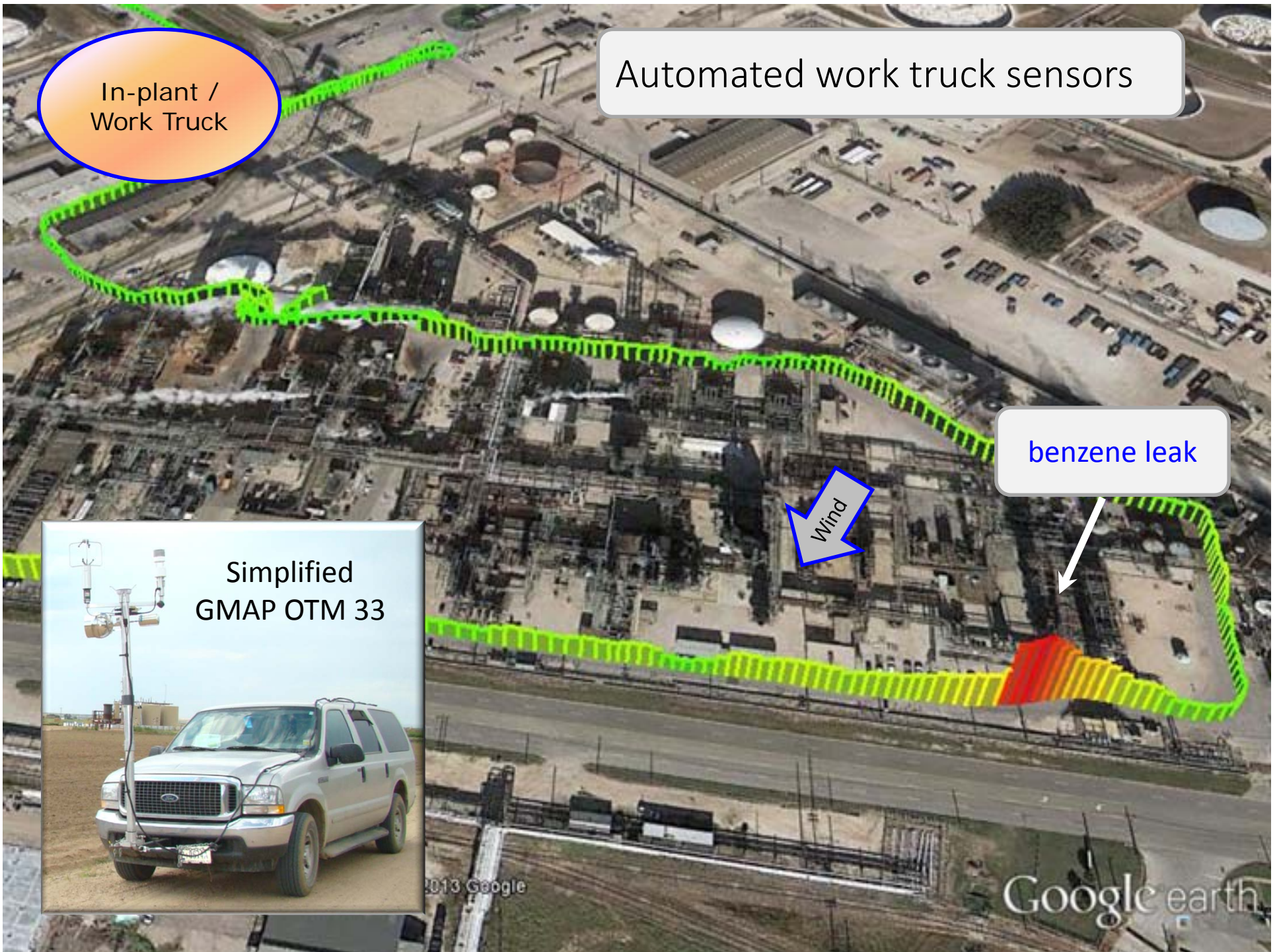
Automated work truck sensors

benzene leak

Wind

Simplified
GMAP OTM 33

Google earth





The Take Home Message

- **We have examined and continue to examine sensors as they become available.**
- **Working closely nationally with South Coast and internationally with the EU**
- **We are integrating these technologies into a variety of research projects**
- **Investigating lower cost (< \$2500) as well as mid-tier (\$3000-\$10000) sensors**
- **Wide range in capabilities. Cost is not necessarily the driver in performance.**
- **Low cost sensor performance is as follows Ozone>PM> CO> NO2>SO2**
- **Very limited low cost options for toxics, VOCs, ammonia, hydrogen sulfide, methane**
- **Source monitoring efforts like the SENTINEL and S-PODs are highly promising**
- **New data visualization tools like RETIGO are now available for use**
- **Village Green Project giving EPA/Regions/Communities immediate access to continuous environmental data using sustainable technology**
- **Demand to understand this technology sector is only increasing in intensity**
- **Health messaging from high frequency data is a BIG issue**
- **Application requirements determine data quality needs and thus instrumentation**
- **Working with device makers on establishing data standards**

Thank You

One resource for you is the following website:

(<http://www2.epa.gov/air-research/air-sensor-toolbox-citizen-scientists>)

