Seminar at Virginia Commonwealth University
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Next-generation air measurement technologies

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Foreword

- The goal of this presentation is to give information on the following topics:
  - Technical perspective on next-generation air monitoring technologies
  - Potential application of sensors
  - Sensor data communication (and concern)

  This presentation is to the public and would be useful for a technical or non-technical individual wanting to understand the state of science on air sensor technologies.

EPA

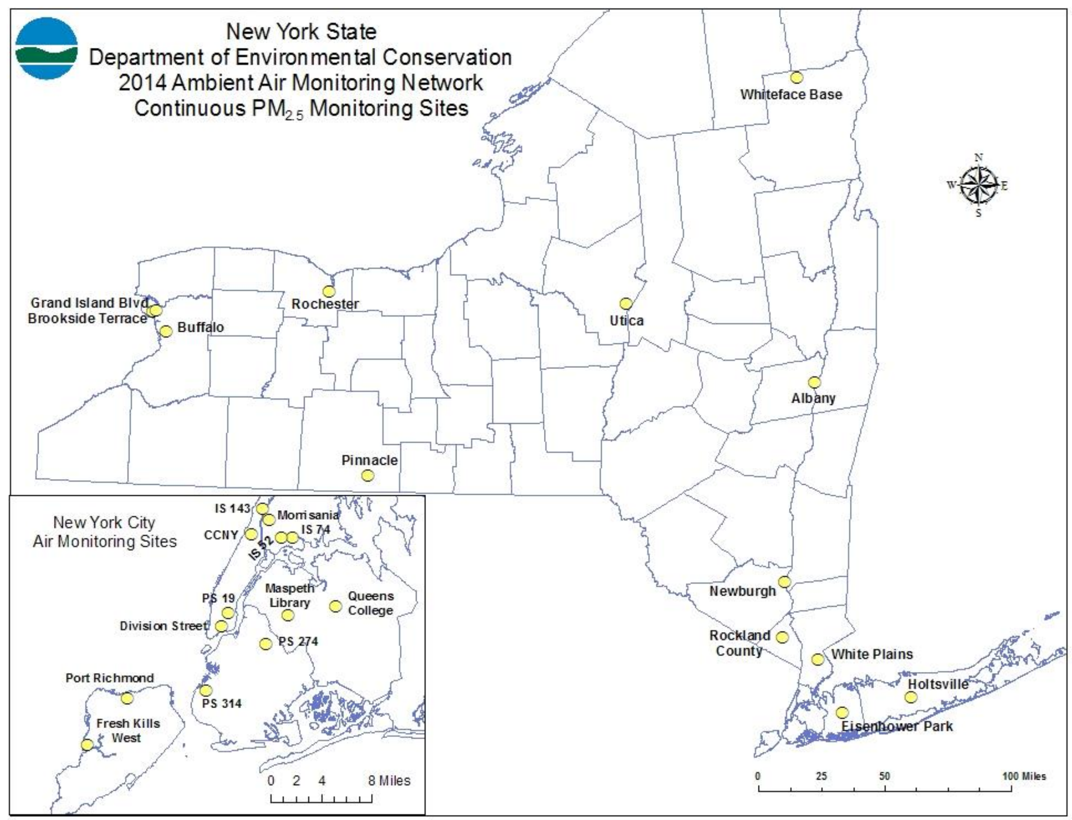
Measuring the air

In the United States, traditional paradigm for air quality monitoring:

Rigorous protocols and methods for regulatory applications

- Expensive instruments (>$10K)
- Specialized training required
- Large physical footprint
- Large power draw

Example: Measuring fine particles in New York



Map from: dec.ny.gov

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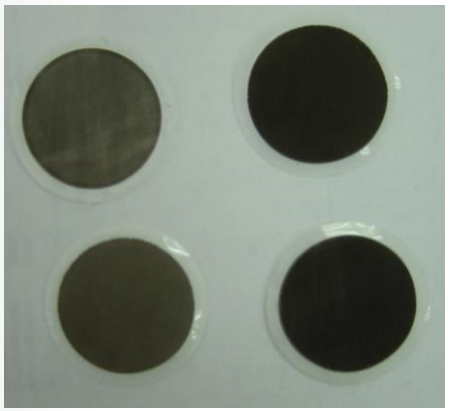
Particulate matter (PM)

Detecting particles: well-established methods

Particle filter samples



<u>Regulatory</u>

Mass (gravimetric)

<u>Additional useful measurements</u>

Ions

Metals

Organic and elemental (aka "black") carbon

Trace organics

Light absorption (transmissometry)

Real-time or near-real time detection of <u>components</u> – <u>most</u> fairly costly (>>10K), required specialized knowledge

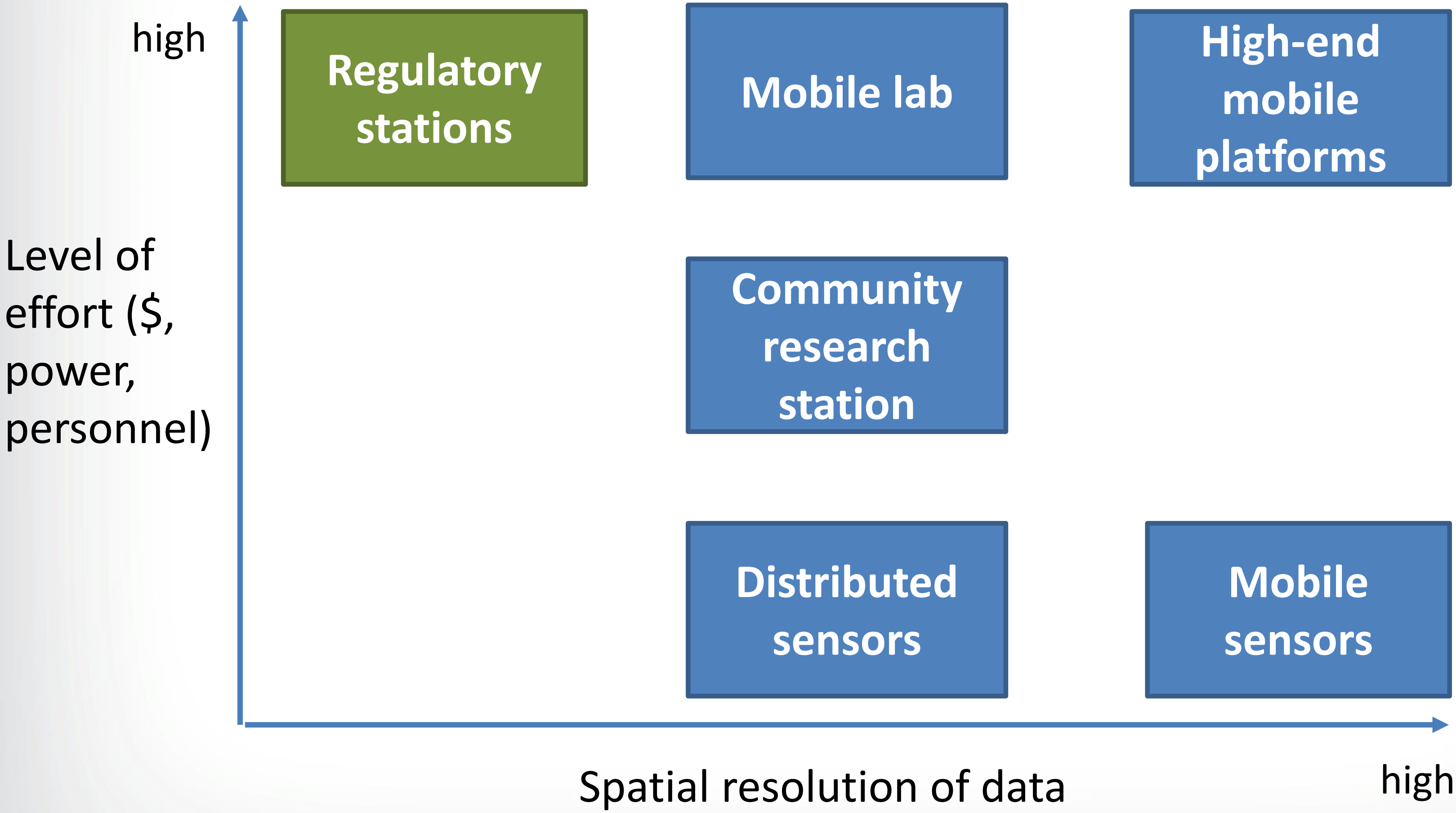
Exception (<10K)

What do we mean by "next-generation air measurement technologies?"

Generally, traits of:

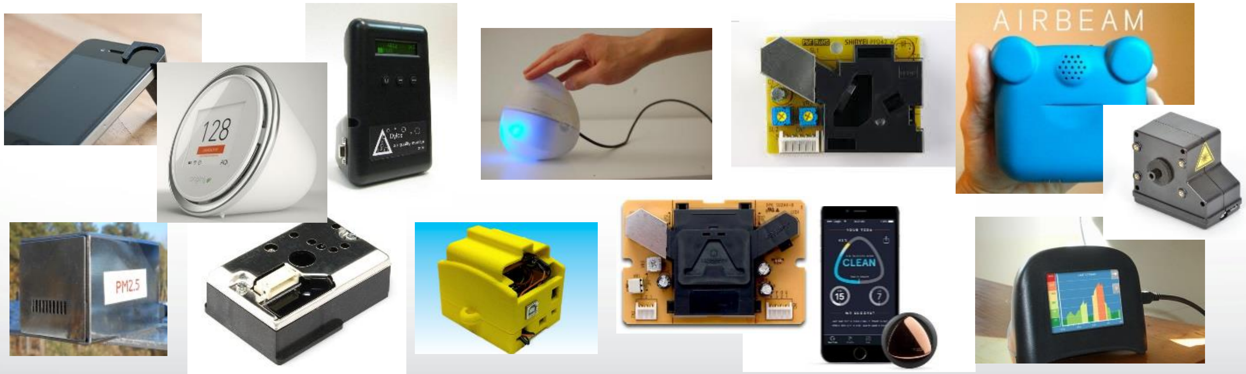
- Greater spatial coverage (mobile, distributed sensors)
- Greater temporal coverage (real-time measurement)
- Cost-effective

Emerging technologies to measure the air



Lower-cost PM measurement methods

Existing, commercially-available PM methods in the mid- ($2-10K) to low-cost (<$2K), and ultra-low cost (<$500) range

	"Estimated, total PM"	**"Particle component"** Black carbon
MID-COST	   	
LOW-COST	  	<N/A>
ULTRA LOW-COST		<N/A>

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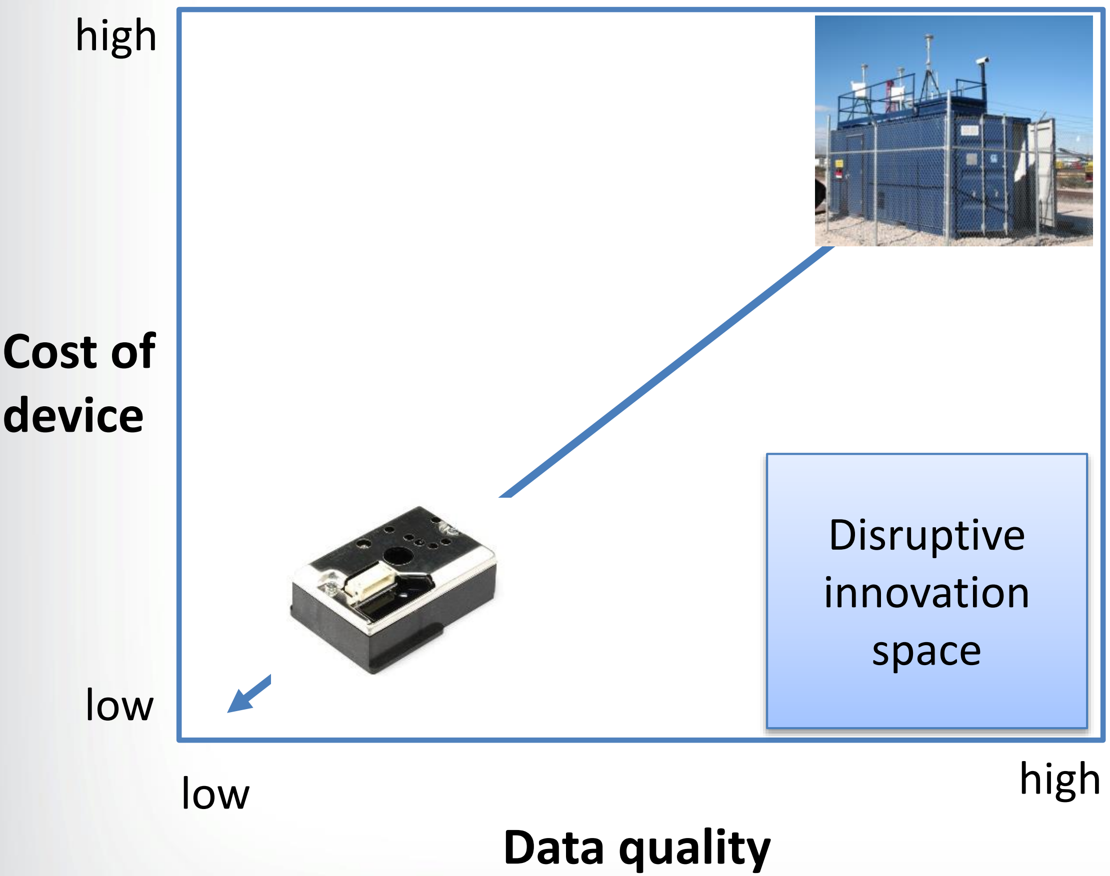
What is the difference?

What is the difference between regulatory instrument, traditional research instruments, and emerging sensors?

Trait	Federal equivalent method	Mid-tier cost research instrument	Low-cost, emerging air sensor
Cost	~10-20K	~5-10K	~0.02K (or ~$20)
Isolates particles under 2.5 microns?	Yes – cyclone removes PM greater than 2.5	Yes – cyclone removes PM greater than 2.5	**No**
Active air flow?	Yes	Yes	**No**
True mass measurement?	Yes – e.g., beta-attenuation	**No – light-scattering**	**No – light scattering**
On-board humidity artifact correction?	Not needed	Yes	**No**
Data time resolution	**Hourly (or longer)**	Seconds to minutes	Seconds

Can math overcome what is sacrificed in the measurement?



Researchers using advanced data processing strategies to get meaningful information from low-cost (~$20) sensors:

"We're compensating for a bad sensor with machine learning..."

- Illah Nourbakhsh, sensor developer at Carnegie Mellon University, during a recent interview

"...**a separate model was selected for each sensor....Fifth order polynomial models** that included relative humidity (RH %) and temperature (C) was found to best convert PUWP signals into $PM_{2.5}$..."

- Gao et al., 2015, A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of $PM_{2.5}$ in Xi'an China. Environmental Pollution

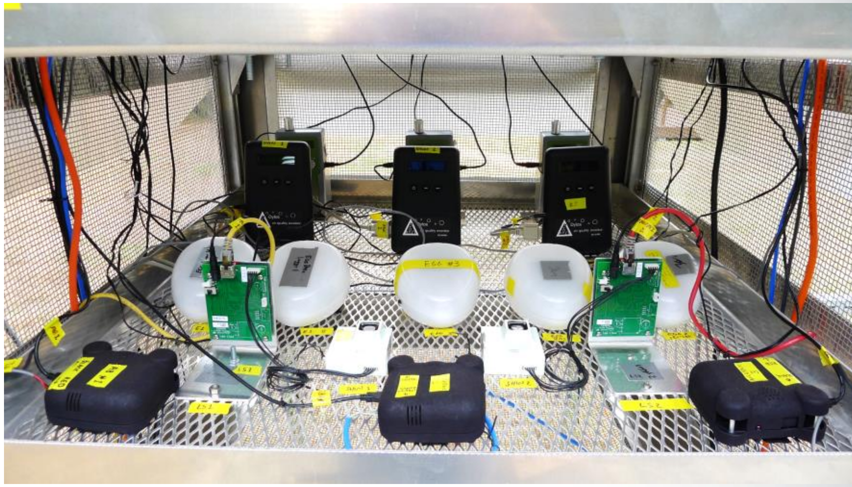
EPA activities

1. Testing air sensor performance in laboratory and field settings

- Atlanta, GA (2014-2015)
- Denver, CO (2015-2016)
- Research Triangle Park, NC (2014 – 2016)

- Emphasis on turn-key devices that are commercially available, measure regulated air pollutants (e.g., ozone, particulate matter), and <2K

- Sensor performance has varied widely – from very strong (r>0.9) to very poor performance (r=0)



Resource: http://www.epa.gov/air-research/air-sensor-toolbox-citizen-scientists

EPA activities

2. Exploratory research studies

- High-concentration environments near sources
  - Example: balloon-lofted sensors within wildfire emissions plume
  - Example: drop-in-place solar-powered volatile organic compounds (VOC) sensor near a source fenceline

- Urban-ambient environments
  - Development of single- or multi-pollutant systems supporting citizen science
  - Development of long-term, resilient community monitoring systems

EPA activities

3. Convening and communicating

- Air Sensor Toolbox: http://www.epa.gov/heasd/airsensortoolbox/
  - Test reports on sensor performance
  - Citizen science guidance

- Workshops

- Community Air Monitoring Training (summer 2015)

A few projects to discuss:

Village Green Project

RETIGO

Upcoming sensor studies

Village Green Project

Village Green Project - Vision

To develop a non-regulatory air monitoring system that would support measurements in more locations and increase engagement with community members.

Key attributes:
- Transparent data collection
- Easier to deploy and lower cost
- Data useful for research purposes
- Engage with community members
- Sustainable

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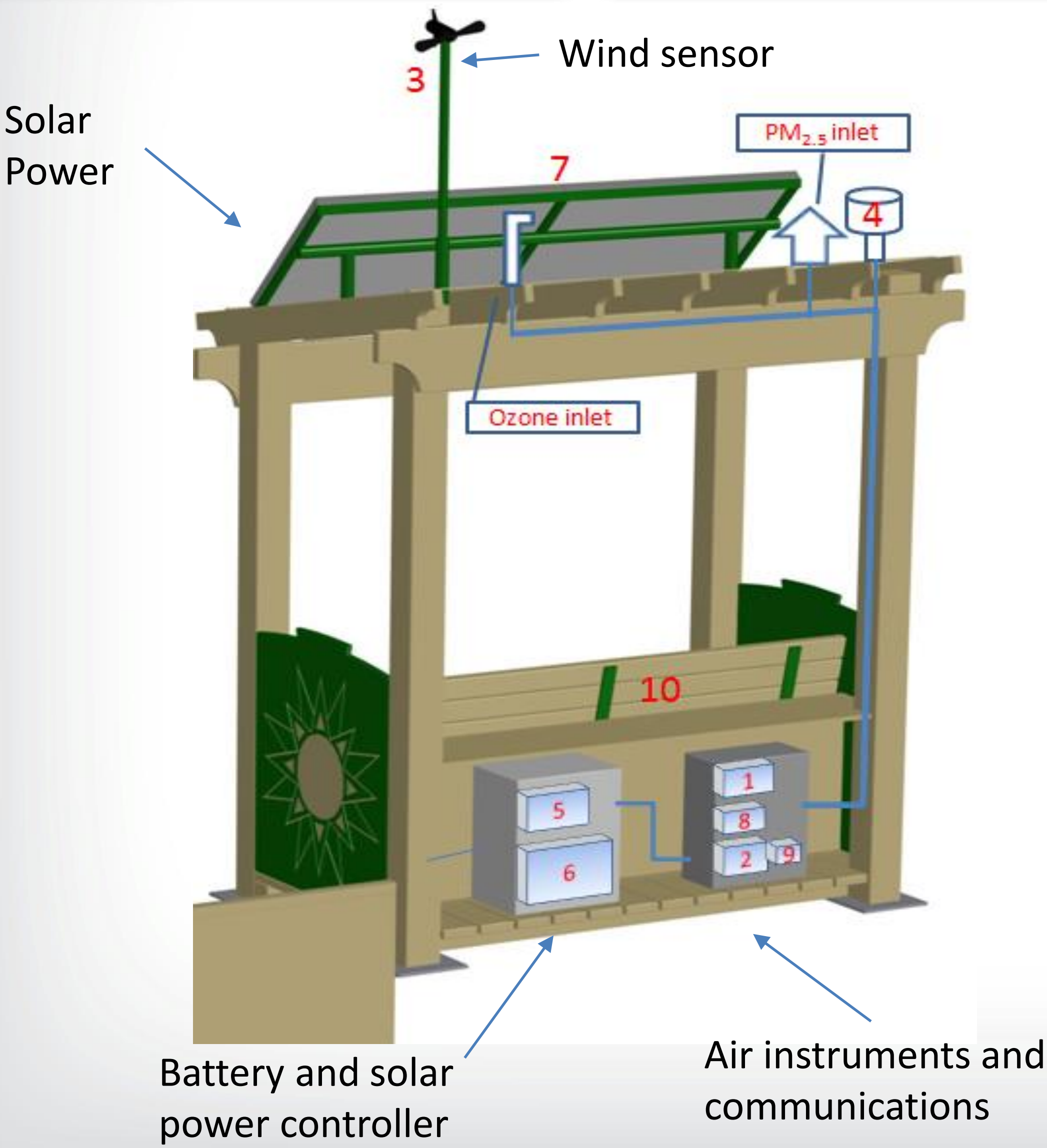
Village Green Project station

- Prototype located in North Carolina, USA outside of a public library.
- 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**
- Self-contained system incorporates
  - **power supply**: solar panels & battery
  - **microprocessor**
  - **cellular modem**

Village Green Project station



- Data quality-checked using algorithms, new data values appear every minute on public website.
- Data values also appear on a sign next to the bench.

A gathering point for community outreach

- Ribbon-cutting ceremony
- Library “Air Fair” and “Science Fair” events
- Tours with local students
- Community presentations
- And…just a place to sit and read.

Prototype test results

- Long-term prototype test in North Carolina (initiated June 2013)
- Sufficient Power from solar panel
  - Power sufficient for ~95% operation time over the first 10 months evaluated (June 2013 – March 2014)
- 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

Jiao et al., ES&T, 2015.

Result: EPA vision of expansion and enhancements

Village Green Project pilot expansion

- USA expansion:
  - Partnership with state and local agencies
  - Competitive proposal opportunity (summer 2014): 22 proposals received, 5 selected for a new station.
  - Additional 1 more station through EPA Region research project.

- Significant improvements made to Village Green Project website and data management system, through the AirNow program.

- Continued technical development of the station:
  - Field-testing a variation of the station in a different range of air pollution through partnership between USEPA and Hong Kong Environmental Protection Department (HKEPD).
  - Testing addition of wind turbine and extra battery to increase system run-time in northern locations.
  - Testing addition of new pollutant sensors.

New stations in USA

Historic area of Philadelphia, PA (installed in spring 2015)

Partners: City of Philadelphia, National Park Service

Press event in April, 2015

New stations in USA

National Zoo in Washington, DC, in the children's farm area (installed in spring 2015)

Partners: Department of Energy and the Environment, Smithsonian Institute

New stations in USA

Outside a public library in Kansas City, KS (installed in spring 2015)
Partners: State of Kansas, Wyandotte County, School District

Station initiation included a ribbon-cutting event and community fair about air quality.

New stations in USA

Location: In the Oklahoma City Myriad Botanical Children's Garden
Partners: State of Oklahoma, Myriad Botanical Gardens

New stations in USA

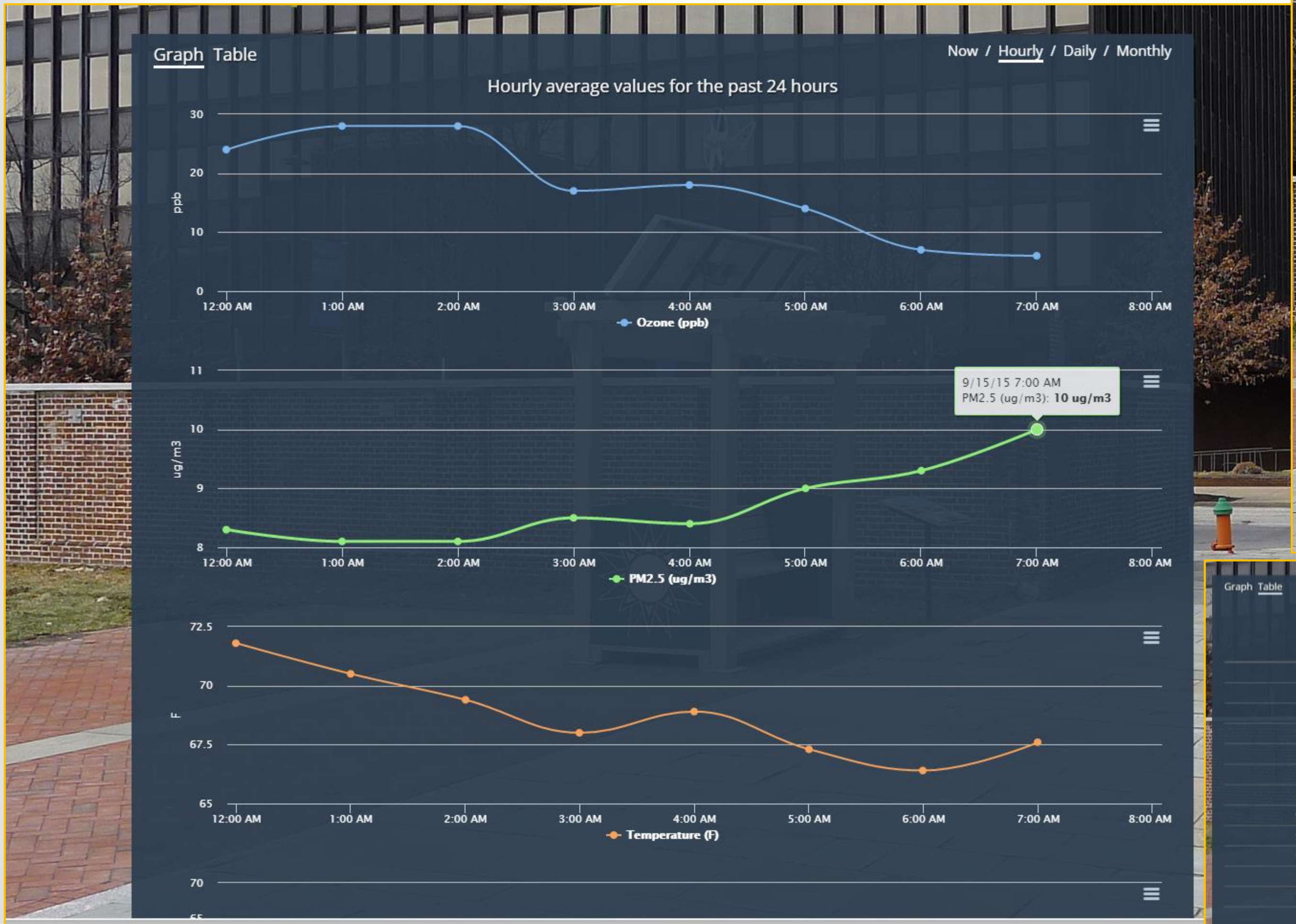
Location: Connecticut Science Center outdoor pavillion
Partners: State of Connecticut, Connecticut Science Center

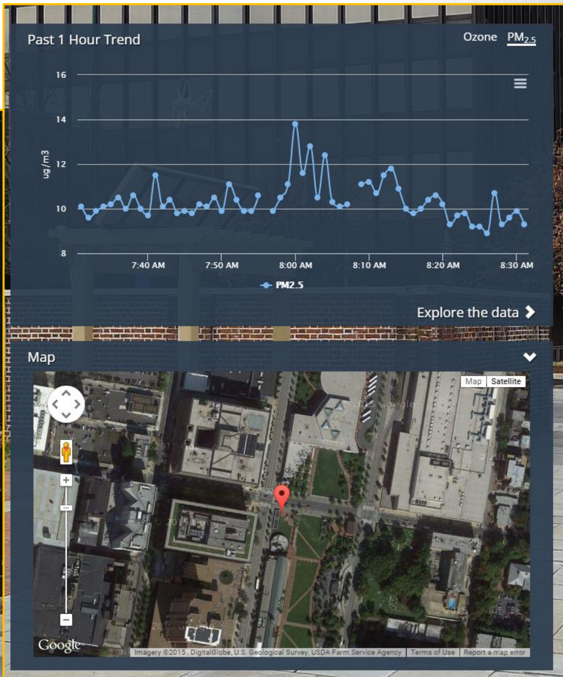
Outreach to the public

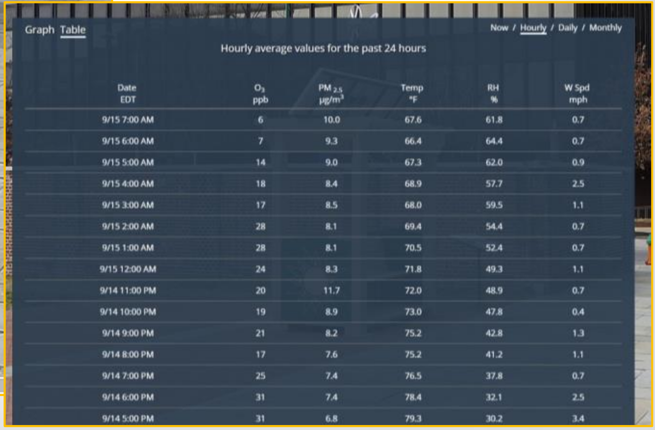
Data website: airnow.gov/villagegreen

Outreach to the public

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

Additional stations in USA

<u>Coming soon</u>

Chicago, Illinois: Station will be located at a public elementary school.

Houston, Texas: Station to be sited at a public school.

Hong Kong station

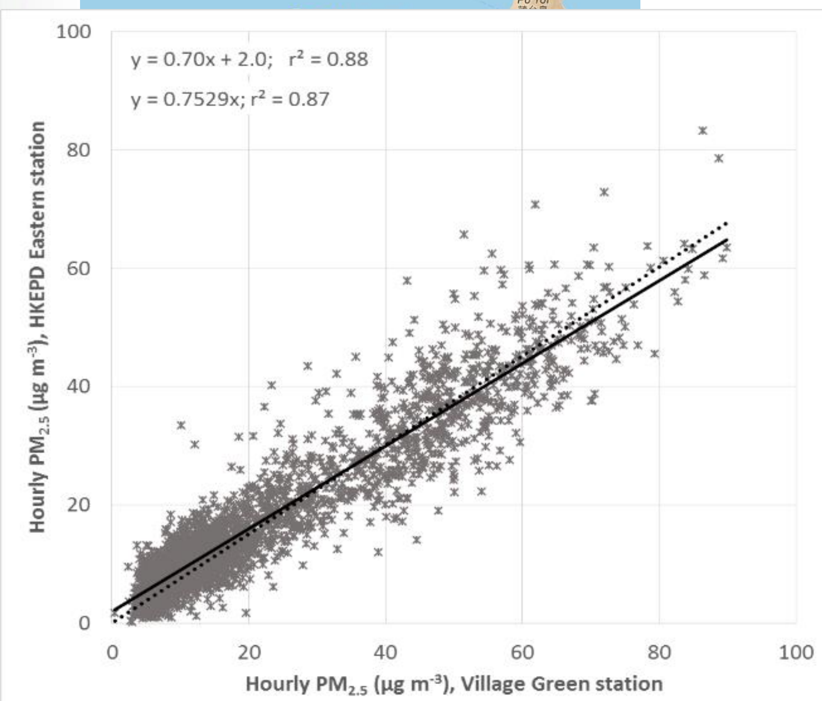
Located on secondary school rooftop
Partners: Hong Kong Environmental Protection Department, City University

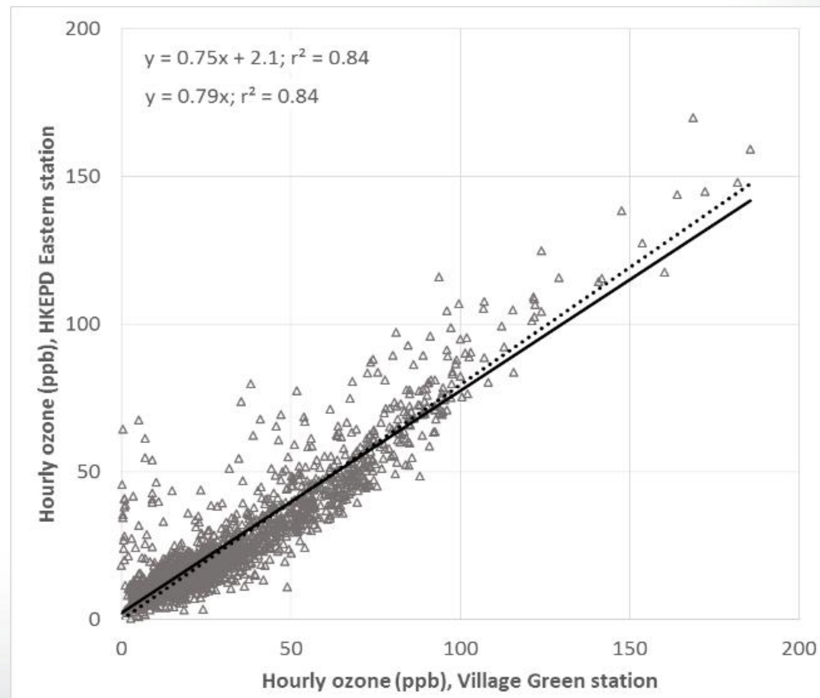
- Same instrumentation in a compact form
- Primary goal: system performance evaluation

Are Village Green systems producing useful data?

Preliminary comparison of regulatory data and Village Green station data sets indicates linearity over observation range.

Concentration range ~2x that previously observed in Jiao et al. (2015) Durham, NC test





RETIGO

RETIGO Background

- Emerging technologies have expanded the requirements of data analysis platforms

Vehicle platforms

- Sampling while driving
- Data rate: 1-10 s
- # variables reported: ~100
- Conducted by: professional researcher

Portable sensors

UC-Boulder

Environment Hamilton

- Sampling while walking/biking
- Data rate: 1-10 s
- # variables reported: ~2-5
- Conducted by: professional researchers and citizens

Distributed sensors

EPA

AQ Mesh

EPA

- Stationary sensors
- Data rate: 1 s – several min
- # variables reported: ~2-10
- Conducted by: professional researchers and citizens

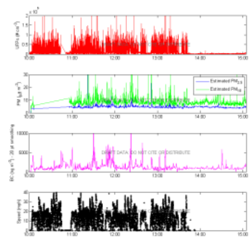
RETIGO Background

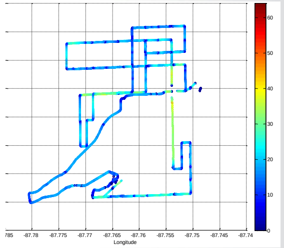
- Emerging data sets are increasingly complex and lack data standardization…
  - Data collection rates are becoming more and more rapid with time. Second-by-second data collection is a target for mobile platforms.
    - 3 hours of 1 second data = 10,800 rows of values
    - 1 second data at 35 mph = ~50 foot travel distance per second
  - Inconsistent timestamps, for example:
    - Sensor 1: time format is Excel serial format (cumulative days since 1/1/1900)
    - Sensor 2: time format is in hours:minutes:seconds, but does not provide a date
    - Sensor 3: time format is in cumulative seconds since 1/1/1899
  - Varying columns of data and units

RETIGO Background

$$\begin{bmatrix} t_1,n_1 & \cdots & t_1,n_{15} \\ \vdots & & \vdots \\ t_{10000+},n_1 & \cdots & t_{10000+},n_{15} \end{bmatrix}$$

- These new measurement approaches provide much larger and more complex data sets to visualize.
- Researchers rely on programs such as MATLAB, IGOR, and R to process and visualize the large data sets using custom scripts
- Some new business ventures create custom visualization apps, but that usually has some limits on individual data exploration and is hardware-specific.





AirCasting App AirCasting Air Monitor

Result: Nonprogrammers, researchers and citizens alike, face a technical barrier to participate in exploratory data analysis.

RETIGO

- RETIGO Project Goal: Reduce technical barrier to participate in analyzing air quality field data, particularly from mobile data collection platforms.

<u>Target attributes</u>

- Non-hardware specific – generic and flexible data input format.
- Comfortable to use for an individual with only intermediate-level experience in Excel.
- Provides interactive data visualization for geospatial air monitoring time series.
- Supports inclusion of complementary web-available data.

RETIGO

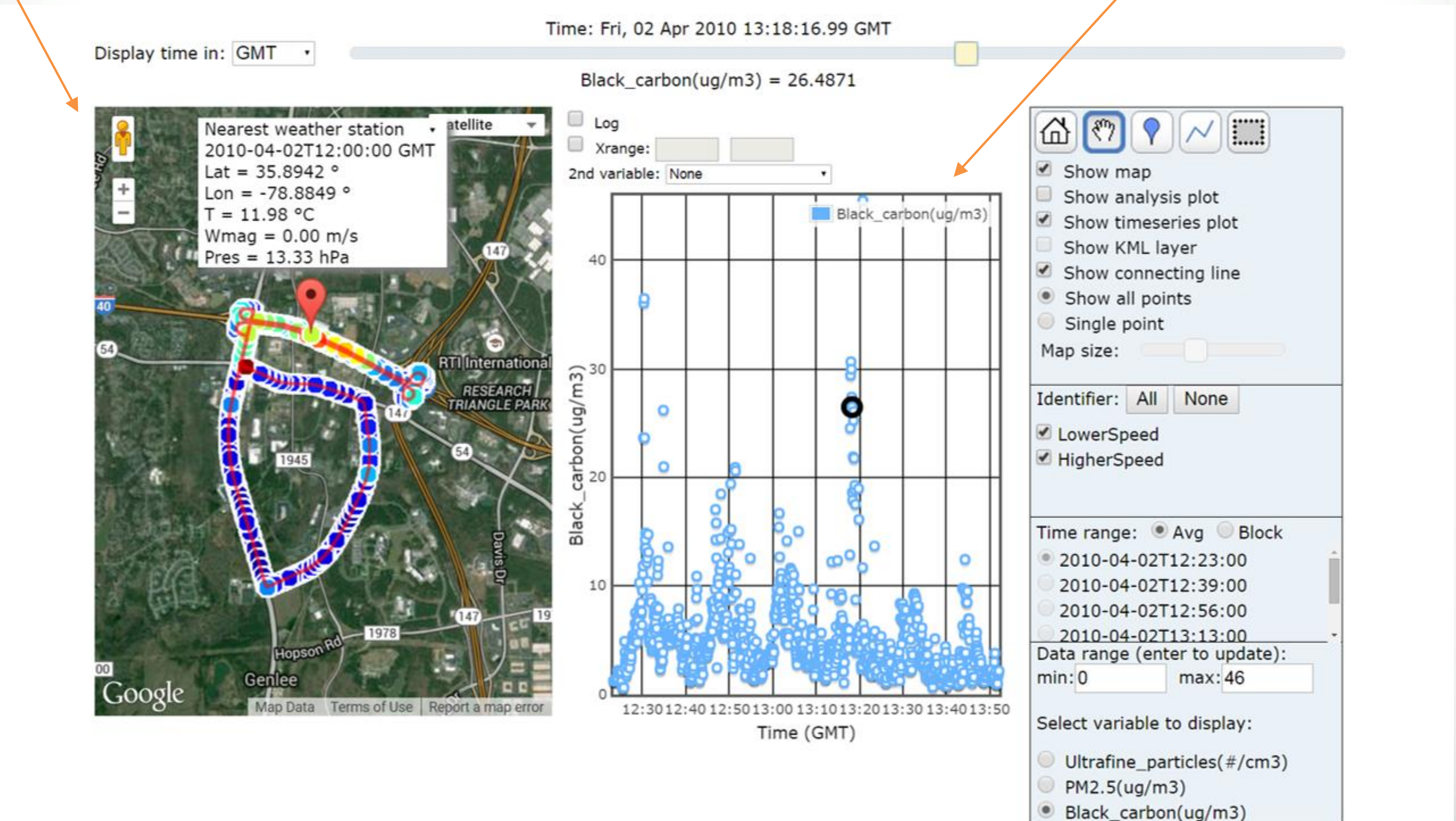
- RETIGO end-user tool:
  - Javascript-based platform
    - Efficient at handling large data sets, creating custom graphics including temporal trends
  - Uses several existing APIs
  - Provides option to input time-matching, location-matching AirNow and World Meteorological Organization weather data
  - Sets a fairly simple standard data input format
    - International time format (ISO1801)
    - Flexible number of input columns
    - Can handle large number of rows (we've tested up to about 200,000 row data sets thus far)

Data visualization

RETIGO: Example view of data uploaded

Map view

Time series



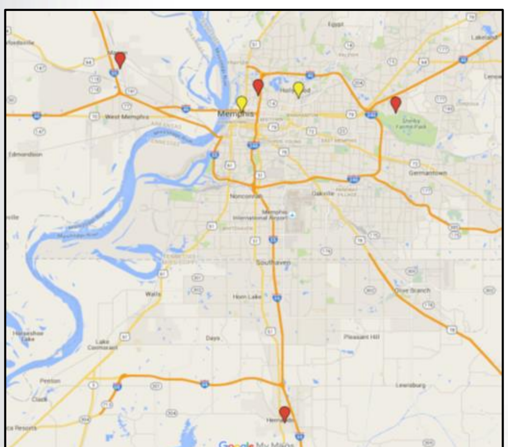
Upcoming sensor studies

EPA

Several upcoming sensor studies

AirMapper:

- Developing portable sensor device for mapping particulate matter trends.
- Integrates an optical particle counter that quantifies particles into 16 size channels, estimates $PM_1/PM_{2.5}/PM_{10}$ with assumptions of particle density and spherical shape.
- Data output in RETIGO format for immediate ability to upload and explore trends.



Current regulatory network

CitySpace project:

- Upcoming research study to deploy up to 20 sensor nodes in Memphis, TN.
- Sensor nodes will include wind and PM sensors, designed for wireless data transmission and continuous operation on solar/battery power.

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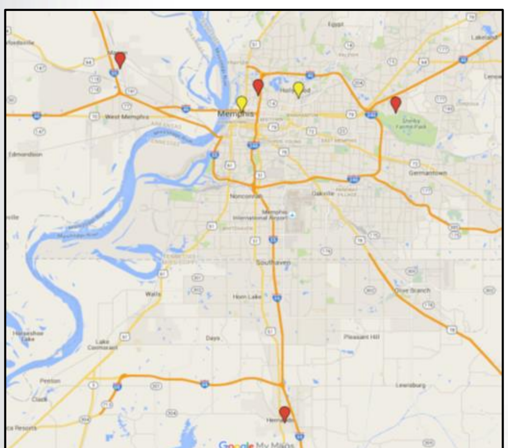

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Summary: Emerging tiers of monitoring

Regulatory

- Reference grade instruments
- Stringent quality assurance
- Usually requires trained personnel
- Usually requires secure structure with air conditioning ($)
- Requires stable land power ($)

What you get:

Highest quality data – can be used for assessing compliance with regulations – e.g., holds up in court of law

Mid-cost system

- Compact instruments
- Trained personnel needed, but hands-on time generally much less
- Monitoring instruments integrated into field-ready structure ($)
- Uses solar and wind power; cellular communication ($)

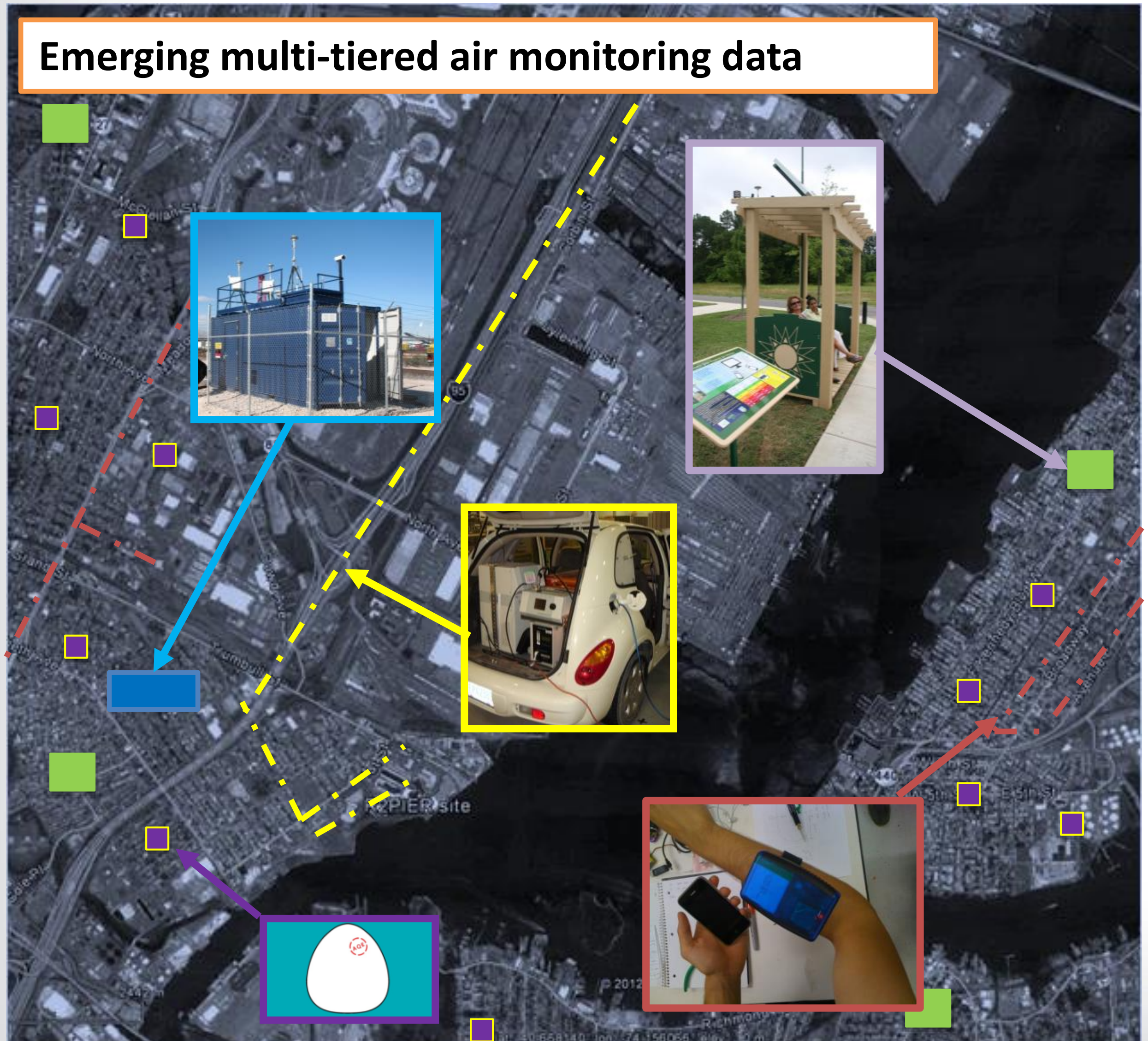
Data agrees within about 10-20% of regulatory instruments (testing in USA) – considered suitable for research studies

Low-cost system

- Miniaturized sensors
- Varying training levels required
- Systems may be field-ready or require significant time to build
- Usually operates on battery power

Data of widely varying quality; recommend R&D to evaluate against reference in field environment

Summary: Emerging tiers of monitoring



<u>Opportunities:</u>

- Unprecedented access to data on neighborhood-scale air quality
- Lower cost strategies to achieve air monitoring goals
- Engagement with communities, schools, industry

<u>Challenges:</u>

- Data quality
- Data interpretation and public messaging
- “Big data” analysis
- Support for do-it-yourself/citizen science

Summary

- EPA is providing leadership in next-generation air monitoring research and engagement with the air monitoring community.
- The research and educational outreach potential is significant, and this technology is developing quickly. Data quality is a major area of concern for EPA.

For more information:

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