Findings from the 2013 EPA Air Sensors Workshop

In March 2013, the U.S. Environmental Protection Agency (EPA) hosted a workshop, entitled *Air Sensors 2013: Data Quality & Applications*, in Research Triangle Park, NC. This was the third in a series of next-generation air monitoring (NGAM) workshops and brought together representatives from EPA, academia, sensor developers, community environmental advocacies, citizen citizens, and state and regional air quality offices. In-person and web-accessed attendance to the workshop included more than 400 registrants and reinforced the high degree of interest being witnessed for this emerging scientific area.

by Ron Williams

Ron Williams is a research chemist with the U.S. Environmental Protection Agency's Office of Research and Development, Research Triangle Park, NC. E-mail: williams.ronald@epa.gov.

The workshop focused on introducing attendees to new technologies, sensor application opportunities, and emerging issues, including how sensors might be evaluated for data quality and/or calibrated during their use, and involved a worldwide search for invited presenters to underline the global emphasis on sensor technologies being exhibited across the globe. The workshop featured invited speakers devoted to four primary topics:

① New technologies, hot science, and instruments on the horizon
② Data quality, evaluation, and calibration
③ Big data, management and analysis
④ Recent applications of sensors

A hands-on technology demonstration was held concurrent with the workshop and included nearly 20 sensor prototypes involving the collection of environmental pollutants ranging from volatile organic compounds (VOCs) to particulate matter (PM). In addition, a diverse poster session was conducted during the workshop and provided sensor developer, citizen scientist, and regulatory officials alike the opportunity to learn more about emerging technologies and their potential use for a wide variety of environmental applications.

To further leverage the value of such a concentration of scientists and interested parties associated with sensor research, a total of six breakout sessions were held that provided attendees with an opportunity to respond to a variety of strawman discussion points developed by the workshop organizers. Breakout groups were led in the following discussions:

① Citizen science and sensors;
② Reducing measurement uncertainty: Calibration approaches;
③ Sensor performance and application guidelines;
④ Designing a sensor information clearing house;
⑤ Big data: Approaches for managing, analyzing, and visualizing large data sets; and
⑥ New technologies: Challenges, data gaps, and needs.

In concert with *EM*, conference organizers will be sharing key findings from the workshop in a series of invited articles; the first four of those articles are published in this issue (articles start on page 6). A second set of six articles will be published in the August 2014 issue. These articles will summarize in their entirety information gleaned from the invited presentations, breakout sessions, and technology demonstrations pertaining to the four primary topics of the workshop. We believe you as the reader will quickly see that not only has the age of sensor development reached a highly advanced stage, the threshold of their widespread use for a variety of environmental applications is on the horizon. **em**

New Technology for Low-Cost, Real-Time Air Monitoring

By Gayle S.W. Hagler, Paul A. Solomon, and Sherri W. Hunt

Gayle Hagler is with the National Risk Management Research Laboratory, **Paul A. Solomon** is with the National Exposure Research Laboratory, and **Sherri Hunt** is with the National Center for Environmental Research, all with the U.S. Environmental Protection Agency's (EPA) Office of Research and Development. E-mail: Hagler.Gayle@epa.gov.

Emerging technologies for air pollution sensing were presented and discussed at the 2013 EPA Air Sensors Workshop, which included a diversity of individuals ranging from sensor developers to air monitoring experts. Novel miniaturized and direct reading detection approaches were presented for particles and gases. In addition, custom devices incorporating ancillary technologies were presented for applications ranging from personal health monitoring to source emissions monitoring. This article describes workshop presentations on sensor technology development and summarizes key areas of needed research and development.

Air quality measurement technology development has evolved along multiple pathways. One long-term trend has been to resolve more precisely air pollution composition and chemistry using complex instrumentation such as real-time aerosol mass spectrometry[1] and online proton-transfer-reaction mass spectrometry[2] developed for optimal measurement sensitivity and time resolution; these techniques sacrifice some attributes that may enable wider use. On the other hand, low-cost air pollution sensors are an emerging air quality measurement technology, with usability attributes (see Table 1)

Table 1. Design attributes of emerging sensor systems.

Key air sensing technology attributes	Additional attributes extending capability (P = personal wearable sensors, F = fence line sensor network, C = community air quality station)
Direct readings	Accelerometry (P)
High time resolution	Global positioning system (P)
Low cost	Biometric sensors (P)
Minimal maintenance	Meteorological sensors (F, C)
Low power demand	Self-healing mesh network communications (F)
Wireless data transmission	Public or private data display (P, C, F)
Turnkey operation	Unobtrusive or value-added design (P, C, F)

and cost guiding the design requirements. At the *2013 EPA Air Sensors Workshop*, attendees discussed a wide range of new applications driving low-cost sensor development, which include personal health monitoring using portable devices that collect air pollution and biometric data, small-footprint air quality stations to assess community exposure, and sensor networks monitoring agricultural and other industrial source emissions. These new desired applications are generating innovation in air quality sensing, with ongoing technology development toward miniaturization, mass fabrication, and direct reading sensors with wireless communication through web-based applications making data available to a wider audience.[3,4]

Emerging Sensors and Sensor Systems

A variety of presentations described novel instruments to meet the need for small, low-cost, and autonomous air pollutant measurements (see Table 2). The most prevalent current approach for particle monitoring is a miniaturized light scattering-based design, with presenters demonstrating the capability of commercially available low-cost sensors, as well as custom light-scattering sensors under development. Light-scattering particle methods can provide indirect estimates of particulate matter (PM) mass for particles in the size range of approximately 0.1–3 µm. Emerging new direct-reading PM mass sensing techniques include microelectromechanical systems (MEMS)-resonator and tuning fork oscillator-based designs, presented by Paprotny et al.[5]and Qin et al.[5], respectively.

Among gas-phase sensing techniques, the most commonly tested approaches presented were metal oxide and electrochemical sensors, however a diversity of other methods were also discussed. Metal oxide and electrochemical sensors are commercially available and their use in air quality studies is made possible through electrical circuitry optimizing the sensor performance, ancillary technologies, and data processing algorithms. Both metal oxide (presented by Piedrahita et al.[5]) and electrochemical sensors (presented by Chaiwatpongsakorn et al.[5]) showed bias due to temperature and relative humidity, which may be correctable via integrated temperature and relative humidity sensors and post-processing algorithms.

In addition to new detection techniques, fully integrated sensor systems were demonstrated that meet particular application needs. Key components include power, communications, and enclosure that vary by application (Table 1). Wearable or handheld sensor devices are generally the most restricted in terms of available power and size. The M-Pod (see Figure 1a) is an example device that utilizes small metal oxide gas-phase sensors integrated into a handheld package that provides battery power and a communications interface with a smartphone app (Hannigan et al.[5]). The ASSIST group at NC State University envisions an even smaller wearable future device that requires only micro-watts of power and solely runs on energy generated by the wearer (i.e., through body heat or motion), powering sensors that provide real-time air quality and biometric data (Muth et al.[5]).

Another example sensor system was built and applied to monitor forest fire emissions in situ. The goal of this pilot study was to cover a large spatial area, utilizing multiple sensor packages to capture upwind and downwind carbon monoxide levels via a metal oxide sensor supported by an Arduino Mega ADK microprocessor, battery power, and XBee radio transmitters (Figure 1b; Johnson et al.[5]). The XBee radio transmitters operate as a self-healing mesh network with long-range capability (~1.6 km line of sight) using the Zigbee/ IEEE 802.15.4 protocol, where wireless data transmission can automatically reroute through other nodes in the network given an interruption at a particular node. Finally, the Village Green Project is a long-term community-based air monitoring station powered by solar panels that wirelessly streams minute-by-minute $PM_{2.5}$, ozone, and meteorology data using a cellular modem to a publically available website (villagegreen.epa.gov). The station was designed to add value to the public outdoor space by integrating the air monitoring equipment into a park bench (Figure 1c; Hagler et al.[5]).

Technology Needs and Challenges

Sensor systems are already being deployed for a wide variety of applications, however most sensor systems have not been thoroughly evaluated and data quality is not well characterized.[4] Determining analytical capabilities of sensors under real-world conditions, including accuracy, precision, selectivity,

Table 2. New detection approaches presented at the 2013 EPA Air Sensors Workshop.

Pollutant	Emerging direct-reading approaches	Related workshop presentations: Presenter's last name / Presentation title
Particles	MEMS with film bulk acoustic resonator†	Paprotny / Microfabricated direct-reading PM mass sensor for personal air quality monitoring
	Miniaturized light scattering†	Bartley / Low-cost air quality monitoring, visualization, and citizen science Dye / A scientist with sensors and spare time: Backyard comparisons of particulate matter sensors Rodes / Advances in particulate matter exposure assessment instrumentation
	Tuning fork crystal†	Qin / Mobile health sensor for personal exposure assessment
	Occlusion of light between optical fibers‡	Mallik / Exploration of novel particulate matter designs
Gases	Metal oxide†	Hannigan / From personal exposure in Boulder to an environmental justice community in Denver to cookstove assessment in Ghana Johnson / Application of low cost sensors to evaluate open source emissions Piedrahita / Validation of low-cost wearable mobile air quality monitors
	Electrochemical (3 or 4 prong) †	Chaiwatpongsakorn / An adhoc wireless sensor network for roadside carbon monoxide monitoring Griswald / Always-on participatory sensing for air quality Vidal / Low power and wireless air pollution monitors Williams / Air sensors evaluation project Zaouak / Cost-efficient miniature sensors for network continuous monitoring of diffuse pollution at the low ppbv level
	Imprinted tuning fork crystal†	Malhotra / Design of an ozone sensing wristwatch using quartz tuning fork oscillators Chen / Wearable and wireless devices for real-time monitoring of volatile organic compounds
	Carbon nanotubes†	Delgado / MWCNT selective benzene detector Font / Selective benzene detection using MWCNT randomly decorated with metal clusters Im / Carbon Nanotube-Based Gas Sensors for Food and Petrochemical Industries
	Organic semiconductors†	Huang / Organic semiconductors as environmental sensors - ammonia case study
	Minaturized gas chromatography†	Bryant-Genevier / Quantitative analysis of multi-VOC mixtures by micro-scale gas chromatography: Recent successes in environmental monitoring and prospects for 'citizen sensing'
	Electrospun composite polymer nanofibers†	Han / Handheld low cost nanofiber sensor for environmental monitoring of VOCs and ozone
	Minaturized non-dispersive infrared sensors†	Johnson / Application of low cost sensors to evaluate open source emissions
	Colorimetric†	Qin / Mobile health sensor for personal exposure assessment

Notes: †Working prototype demonstrated, ‡Conceptual, not at prototype stage yet. All presentations are available at https://sites.google.com/site/airsensors2013/final-materials.

lower detection limits, and measurement stability are continuing challenges for sensor developers, particularly while constrained to meeting desired traits of small-scale and low cost (Table 1).

Lack of facilities, calibration instrumentation, and expertise in air pollution monitoring are also challenges for sensor developers that need to be addressed. Particle sensors for chemical composition (in addition to black carbon content) and ultrafine particles (UFPs, diameter smaller than 100 nm) are a notable technology gap. Current low-cost light scattering or mass-based particle sensors are insensitive to the UFP size range; UFPs have high spatial variability in urban environments[6] and appear to be associated with adverse health effects.[7] Key particle components

Figure 1. Example next-generation air monitoring systems. a) Portable M-Pod device that interfaces with a smartphone app (Photo credit: Ricardo Piedrahita); b) sensor network node during a forest fire emissions event (Johnson et al.[5]); and c) Village Green Project—solar-powered and wirelessly transmitting community station, with inset image showing instrumentation enclosed in the bench structure.

of interest include major ions, elemental and organic carbon, and trace elements as measured in EPA's Chemical Speciation Network,[8] as well as inorganic hazardous air pollutants (HAPS; e.g., As, Be, Sb; www.epa.gov/ttn/atw/orig189.html). Research is currently underway to meet the need for lower cost UFP sensors with network capability (Chen et al., 2013[9]). Among gas-phase sensors, selectivity, sensitivity of response to environmental conditions, and lower detection limits for an individual compound in ambient air are key issues, particularly for trace level volatile organic compounds, a number of which are HAPs (e.g., benzene).

When sensor technology is able to provide sufficient data quality while meeting application requirements, air monitoring practices will likely move quickly to include sensor-based networks with wireless communication. This new technology will provide source assessment, exposure, and health effects researchers with a wealth of new information that may allow for more effective reductions in pollutants of most concern as well as empowering the public with information they can use to make decisions to reduce their personal exposures. **em**

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Low-Cost Sensor Calibration Options

by Ron Williams, Tim Watkins, and Russell Long

Ron Williams, Tim Watkins, and Russell Long are all with the U.S. Environmental Protection Agency's (EPA) Office of Research and Development, Research Triangle Park, NC. E-mail: williams.ronald@epa.gov.

Low-cost sensors ($100–500) represent a unique class of air monitoring devices that may provide for more ubiquitous pollutant monitoring. They vary widely in design and measure pollutants, ranging from ozone, particulate matter, to volatile organic compounds. Many of these sensors provide for continuous air quality measurements and wireless data transmission. However, data quality from such devices is a concern. Three straw-man approaches to improve upon the usability of such measurements were considered as part of the 2013 EPA Air Sensors Workshop. Findings from the breakout devoted to this topic are summarized below.

The *2013 EPA Air Sensors Workshop* had a primary goal of moving past previous expert discussions on discovery of low-cost sensor technologies[1,2] to how data from such sensors could be used to their full advantage. One key concern about these technologies was the uncertainty of their data, in that often no direct means of sensor calibration was being provided by the sensor developer. As explained further in this article, there are a multitude of reasons for this lack of what most monitoring experts would consider to be a necessary feature of any air quality sensor (user response calibration).

This leaves the user (often private citizens with no scientific training) with collecting data which may or may not be accurate or even realistic. To help frame a discussion about this concern and how it might be resolved, three straw-man calibration approaches were developed prior to the workshop. They were provided to registrants in advance for their consideration. Subsequent breakout panels consisting of more than 40 experts with backgrounds in sensor development, environmental monitoring, regulatory affairs, data signal processing, or citizen science then critically examined each straw-man approach. The value of each approach was considered and summary conclusions established based upon the likelihood of success of each approach and/or its acceptance by the lower cost sensor user community. Key features of each approach are defined in Table 1 and discussed in depth below.

Option 1. Use of a signal-based (wireless) calibration technique

State and federal air quality monitoring platforms are often collecting (and some even reporting) near real-time gas and particulate matter concentrations of select air pollutants via local (state) or federal (AirNow) venues. If it was possible to obtain telemetry from these monitoring locations and broadcast it to the surrounding area it would provide the means for receiving units (wireless-based sensors) to perform single point calibration of their response. Such telemetry might be broadcast using a local signal (typically within 500m of the transmitter) and would require potential "users" of the calibration data to travel to the site to acquire the data. The local air monitoring station operator would have to agree to share their output data in real time. It is uncertain who would provide resources to broadcast the signal to others. An alternative would be to simply have "users" acquire data from the nearest available website, which would have some degree of data relay impact between the actual measurement time and its public reporting (expected to be >5 min time delay). How might such options be advantageous to users?

If users had the means of zeroing their device

Table 1. Potential low-cost sensor calibration options.

	Option 1	**Option 2**	**Option 3**
Key calibration feature	Wireless signal	Direct sensor calibration	Secondary data normalization
Panel ranking (option most preferable)	Low, but has been shown to be feasible	Highest for those involved in regulatory monitoring	High. Deemed most practical as it is already widely performed by professionals
Positive features	Calibrations could be performed on the go and take advantage of regulatory air monitoring station data	Ensures greatest level of confidence in data quality. Represents the traditional gold standard practice	Commonly performed among environmental professionals. Allows "sanity check" of data quality
Negative features	Monitoring stations would have to provide signal and sensors would have to have the means of receiving and using this signal	Economically less reasonable. Non-professionals probably not qualified to perform calibration procedures	Non-professionals may not know where to obtain verified data or how to normalize data using mathematical functions
Intangibles (including cost comparison)	Would require infrastructure to acquire and broadcast calibration signal. Most expensive cost option ($$$)	Sensor developers are limiting user access to calibration algorithms for practical reasons. Relatively inexpensive to perform after original items purchase ($)	An application could be developed that assisted novice users in data normalization but no lead for doing so currently exists. Moderate expense to perform ($SS)
Likelihood of advancement	Doubtful infrastructure can be developed due to economic constraints	No impetus for developers to provide calibration kits. Sensors considered disposable	Likely. Only modest resources needed for a publically-available data normalization application

immediately followed by offsetting the response based on the output from the local air monitoring station it would yield a zero and span approach that should be inherently more valuable than doing no calibration check at all. It would, however, be limited to the scale of the pollutant concentration encountered (with a potential lack of data at either the high or low detection range of the sensor resulting in less than a full understanding of the true linearity impact across the sensor's full range). A key feature of this approach would be the need for sensor developers to develop a built-in process by which a calibration signal could be received and then automatically processed. This would seem to be a fairly simple process but most of the effort to date would appear to be on the theory of such an approach with only limited examples of such attempts.

Option 2. Development of low-cost (direct) sensor calibration kits for sale/distribution to sensor developers/users

It is recognized that the direct calibration of a sensor would be the gold standard. Such a calibration approach might involve either one of two techniques: (1) challenging the inlet or contact surface of the sensor to a gas of known concentration, or (2) in the case of sensors having some defined response (e.g., resistance/conductance, voltage), activating a circuit that would establish some predefined output and would, in turn, establish the concentration readout of the device. We considered each of these separately with discussions focusing on gas-phase sensors (e.g., CO, NO_2, O_3). It did not seem practical to consider either of these techniques for calibration of particulate matter-based sensors.

One primary positive outcome from directly challenging the sensor surface with a gas of known concentration (technique #1) is the assurance that the challenge condition is well defined. One knows the concentration and purity of the gas being applied, that direct contact of the gas and sensor interface is occurring, and that one might be able to maintain the residence time of the gas on the interface to overcome response (delay) features. Calibration gas bottles are relatively inexpensive (high purity gas in small portable bottles typically can be obtained for ~ $100) and there is already an infrastructure (vendors) who produce and sell such bottles in a wide variety of single as well as multiple gas concentrations.

Many of the low-cost sensors being widely distributed for both the lower cost, as well as the mid-range sensor market, have response curves established not on the basis of a direct chemical challenge at the time of their sale, but on the basis of a theoretical response of a batch or production example. Therefore, if one establishes an electronic or electromechanical means (technique #2) of challenging the sensor to a known effect (resistance/conductance, etc.), the resulting output of the sensor (reported environmental concentration) could be rescaled to some pre-established value. Of course, one would have to know what the theoretical response is supposed to be based upon manufacturer's specifications. Both of the techniques being considered would be dependent upon the user having the skills and necessary supplies to conduct the calibration.

Option 3. Use of collocated data from more recognized (Federal Reference Method/Federal Equivalency Method or research grade) monitors to normalize response

State and federal air quality monitoring platforms often collect a wide variety of pollutant measures. These include the criteria gases (CO, NO_2, O_3, SO_2) and particulate matter. If one did not have the ability to consider either technical approach options 1 or 2 as defined above, a third approach would offer the means of converting raw (non-calibrated) data into that of more acceptable quality. Data (either with short time resolution or that with longer integration periods) from state and federal air quality systems could be obtained and then used to normalize archived lower cost sensor output. Such an approach would not require lower cost sensor developers to reconfigure hardware/software to accept a direct chemical challenge or circuitry to mimic some pre-set response criteria. Therefore, the cost of developing lower cost sensors would remain relatively low.

Such an approach would be predicated on a number of factors which the end user would not be able to control. These include: (1) assurance that a sufficient degree of vetted data from the reference source was available during the time period of interest; (2) the delay in acquiring the reference data and then applying it mathematically to the raw data could be substantial (days to months) and therefore the ability to use the lower cost sensor data as a quick screening tools would be hindered; and (3) the end users would need the ability to obtain the reference data and then apply it correctly to normalize the raw response.

Summary Findings

It was obvious that there was no perfect option in developing a recommended calibration approach for low-cost sensors. In fact, some participants felt strongly that a mixture of the three options might be required. Those involved in regulatory monitoring felt strongly that direct sensor calibration was mandated (Option 2). Attendees who had some experience in use of a wireless calibration approach (Option 1) indicated that it was not only feasible but was being done as part of one on-road fleet ozone monitoring program.[3] If one approach was viewed as the default method that could always be applied it was Option 3. Normalization approaches are widely used (even in high grade research study designs) and would not require sensor developers to invest heavily in new hardware/software designs.[4] Likewise, it would not require an investment in calibration signaling hardware/software from resource-limited air monitoring networks. Regardless of the option selected, it is recognized that low-cost sensors will probably have a limited lifetime (expected to be less than 2 years). During this time, the output of the sensor's data acquisition board will change and thus users must be aware that calibration is not a simple one-time operation.

Many state and federal air monitoring stations are starting to release continuous particulate matter and criteria gas air quality data in near-real time via the Internet. They are not currently sending out wireless based data which might be the source of the calibration signal defined by Option 1. Local micro-environments are known to have a tremendous impact on particulate matter concentrations, so sensor location when the calibration signal was being received could be an issue. O_3 concentrations are very homogeneous over wide spatial areas. If the sensor was away from traffic impacts (minimizing NO_2 and O_3 titration impacts) and outdoors (where it reacts with indoor surfaces), one could expect the ambient calibration point to be very useful in calibrating the sensor. SO_2 would seem to be a reasonable candidate for such a calibration approach and once again, measurements would need to be taken outdoors due to the infiltration loses observed between ambient and the indoor environment. Both CO and NO_2 represent microenvironmentally-sensitive gas pollutants (some degree of heterogeneity due to mobile source emissions). As such, there would need to be careful selection of an outdoor monitoring location for the single point method to be effective and not introduce serious bias into the resulting raw data collections.

After much discussion concerning Option 2 and its technical feasibility, a simple question was asked of the breakout attendees. Would you purchase a calibration kit estimated to cost ~ $100 if the sensor it was to be used upon only cost $200? The answer was near unanimous–no! It made little economic sense to expect citizen scientists to purchase such kits at such a cost ratio and then have the technical ability to use them. Furthermore, sensor developers indicated they did not wish for such users to have the ability to reprogram response algorithms. As one sensor developer noted, "giving the user the ability to reprogram the response would result in only issues. If the sensor started reporting 'bad looking data' the user would automatically assume it was the device (and not the fact that a faulty calibration procedure had been performed)". Furthermore, multiple sensor developers indicated a more practical approach was to simply have the users send in the device for professional recalibration/refurbishment and that a known date of calibration expiration should be issued at the time of purchase. These certification dates should not exceed 1 year in length and in fact, many of the current mid-range sensor developers (<$5,000) often indicate such certification periods. While attendees felt the electromechanical or circuit-based calibration (e.g., resistance) would work for some of the current sensor types, this approach gathered no traction in the

Many state and federal air monitoring stations are starting to release continuous particulate matter and criteria gas air quality data in near-real time via the Internet.

discussions and was quickly dismissed as less likely to be developed by sensor developers.

The simplest of the mathematical models that might apply to an Option 3 approach would be use of a linear equation relationship (y = mx +b) where the slope (m) and intercept (b) of the resulting raw versus reference data would be compared.[5] An equation like this is the primary means of establishing the degree of agreement between Federal Equivalency Monitors versus Federal Reference Monitors. The resulting slope and intercept are then used to re-establish the "true" response of the raw data. However, it must be recognized that many of the low-cost sensors do not have a linear response (or may have a linear response for a specific range of their overall response curve. Therefore, it will never be a one-size-fits-all approach and curve-linear relationship curves would need to be established. More importantly, the end users would have to be able to recognize that: (1) the data being compared was not of a linear nature, and (2) that one of the many various curve-linear models would have to be selected and then applied to the raw data. It would be expected that many lower cost sensor users would not have the technical ability to select the appropriate curve to apply. Likewise, end users having only modest technical backgrounds may balk at having to perform such efforts which would result in some degree of preventing them from reporting/using the raw data they have acquired. It was agreed that there would need to be some third party application (software) that would walk lower cost sensor users through raw data input, reference data input, appropriate curve selection, and ultimately recalculation of raw data its final form. No one was able to identify who should be responsible for such an application.

One approach that was not a part of the straw-man discussion but which was volunteered was "machine learning". This technique would use host-based processing of sensor data streams and mathematically (statistically) search out data values that appeared out of range. Data would be self-normalized (within the monitoring network) rather than any sensor calibration per se. It was agreed that such an approach, taken to its fullest potential, would eliminate the need for any of the straw-man options and help introduce "sanity checks" into overall data quality and probably represents the future of ubiquitous sensing data mining.

One common concern about such an approach is that data viewed as abnormal (low or high) with respect to its peers, might in fact, be accurate and thus eliminated from use. Micro-environmental hot spots are known to exist (e.g., near road traffic emissions, combustion sources, etc.) with widely fluctuating pollutant concentrations which would need to be considered in any machine learning application. Machine learning has been applied to large sensor networks involving such measurements as meteorological parameters.[6] However, one would have to develop a systematic approach (infrastructure) for acquiring sensor data and then processing it. No such public or government infrastructure exists in the United States. However, some European municipalities are involved in establishing such infrastructure and so the concept appears to be one more of economic rather than technical considerations.[7] **em**

Acknowledgment: The authors wish to thank all of the attendees who participated in the workshop breakout sessions devoted to data uncertainty and calibration options; Sarah Bereznicki and Fu-lin Chen are thanked for their review of the article. The research described here has been subjected to EPA review and approved for publication.

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Air Sensors

Big Data, Big Dreams

by Vasu Kilaru

Vasu Kilaru is a physical scientist with the U.S. Environmental Protection Agency's (EPA) Office of Research and Development, Research Triangle Park, NC. E-mail: kilaru.vasu@epa.gov.

The term "big data" is quickly becoming part of the scientific, business, and daily lexicon. Various disciplines and enterprises have embraced the concept in an attempt to push innovation and discovery in a world where ever increasing amounts of data are available. While, in theory, there seem to be clear benefits, the ability of organizations to ingest, process, and create knowledge from vast streams of data are not trivial. What "big data" means and its implementation in other contexts may help us understand how it can be applied to the field of air sensors specifically, and environmental data in general.

Over the past several years, a new term has emerged from the esoteric information technology lexicon to become almost common parlance. "Big data" is now being discussed not only in journal literature, but in television commercials. Some of the claims and benefits may be hype, aimed at the presumably deep pockets of chief information officers (CIOs), but the reality of ever-increasing data everywhere is far from fiction. Data historically have been difficult to locate and expensive to obtain, but with the advent of computers, and ever smaller and inexpensive devices, we are now in an age of data deluge. So, what exactly is big data, and more specifically, what are the implications for environmental data from air sensors? At the 2013 EPA Air Sensors Workshop, we aimed to introduce attendees to the term and some of the aspects it touches.

Defining Big Data

The National Science Foundation (NSF) has embarked on a multi-million-dollar program to fund research in big data, which NSF defines as: "…advance[ing] the core scientific and technological means of managing, analyzing, visualizing, and extracting useful information from large, diverse, distributed and heterogeneous data sets so as to: accelerate the progress of scientific discovery and innovation; lead to new fields of inquiry that would not otherwise be possible…."[1]

A more business-oriented definition might be: "…an enterprise that can mine all the data it collects right across its operations to unlock golden nuggets of business intelligence…."[2]

Some estimates put worldwide data generation at 2.5 Exabytes per day[3]—that is equivalent to a stack of 2 Terabyte hard drives almost 20 miles long.[4] While we may not be interested in this all-encompassing definition, even within the confines of a discipline or enterprise, the entirety of relevant data may still be substantial and growing fast. Big data, even in the realm of science, varies with discipline and presents challenges not only with regard to the size of data sets, but also in the diversity of data being integrated.[5]

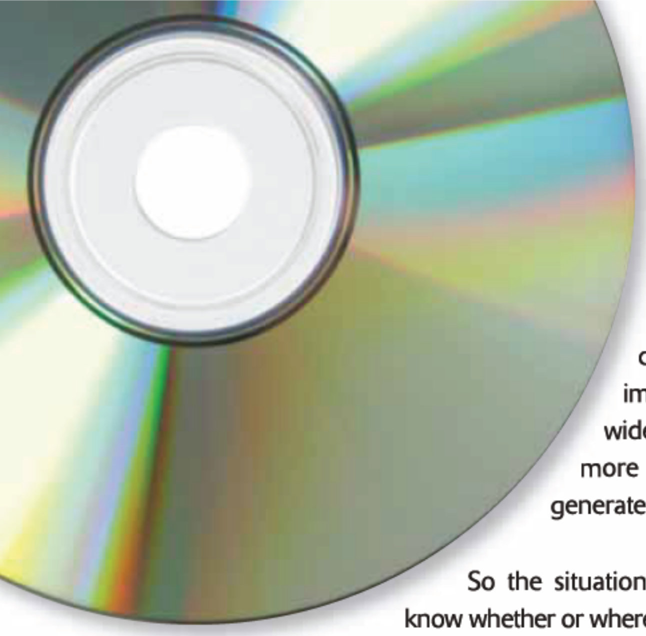
Genomics offers a prime example of the radical change that data has made to the discipline. The first bacterium cost billions of dollars to sequence and years to analyze, but now a personal genome can be mapped in a few days for around $1,000.[6] Sequencing costs are plummeting by 50% every five months, making enormous amounts of data available.[7] With hard disk storage costs (MB/$) only doubling every 14 months, the result is that next-generation sequencing technology is outpacing the computational resources to store, process, and manage data.[8] So while sequencing originally dominated the cost structure, now the costs being incurred are in data management and downstream analysis.[9]

This has resulted in the genomics community desperately and rapidly attempting to transform the way data collection and science take place by creating a, "platform which supports an ecology of databases, interfaces, and analysis software."[10] The ultimate goal being: to allow users flexibility in access to tools, data, and resources, in a scalable cost-effective manner, that provides incentives to share in the process of discovery.[11] While data streams from air sensors may not constitute the levels of data generation in genomics, challenges nonetheless still exist in other aspects such as quality, sampling protocols, and integration of disparate data sets.

Locating the Data

One of the first steps in such an endeavor is knowing the existence of relevant data. The data we need may exist, but if we don't know of it or can't find it, it is essentially useless to us. While the concept of data discovery may seem obvious and philosophical arguments of epistemology notwithstanding, the issue of how and whether we can find data is central, critical, and nontrivial to the ability to utilize them in further analysis. In addition, data and information may not reside where we like, or be available in forms we desire, or generally be in a state for us to readily ingest or process.

Still a further complication is that, in general, there are two broad categories of data: structured and unstructured. Structured data are highly organized



data sets such as relational databases where structured queries can return the needed data. Unstructured data includes such things as text, images, and video and are widely thought to represent more than 85% of the data generated. [2]

So the situation may be that we don't know whether or where the information we seek exists, or if it does exist, we can't readily find it. If we do find it, access and format may be too onerous. Finally, the nature of the information (unstructured text and images) may prove too difficult to deal with and process. In the context of air sensors, the ability to discover new data sources in a distributed environment and be able to integrate that information to address a given problem will be require a large shift from the current centralized air pollution monitoring paradigm.

The format wars of VHS versus Betamax or DVD versus Blue-ray are testaments to both the promise and pitfalls of technology adoption and market penetration.

Setting Standards

An obvious way forward from big data's four Vs—volume, velocity, variety, and veracity[13]—is by way of standards. Standards essentially provide some basic structure with which to base queries for information. This is especially important given that most data are unstructured. We have touched upon the volume and velocity of data, variety is just that, a diverse set of data elements from various sources that contain information potentially important to an endeavor. And as was discussed elsewhere at workshop, veracity, in some ways, may be the most important, since it represents the accuracy or trustworthiness of the data. Without some confidence on the quality of the data at hand, it is very difficult to draw any conclusions or place any confidence bounds on estimates. Again standards can help if we adhere to them.

The Open Geospatial Consortium (OGC) has developed a number of standards related to sensors, namely Sensor Model Language (SensorML), Sensor Web Enablement (SWE), and Sensor Observation Service (SOS).[14] If conformed to, these standards not only make finding data easier, but also greatly ease the creation of third-party applications that utilize the data.[15] This allows not only measurements to be democratized, but so also the applications. Given standards and an application programming interface (API), anyone can build an application to query, retrieve, and utilize data.

Standards also allow for more modern collaborative software designs such as, Service Oriented Architecture (SOA). SOA allows for pieces of self-contained code that perform certain functions to be shared and combined with other SOAs.[16] But standards are notorious for being static, not flexible, and sometimes operationally onerous. The ideal standard needs to have a form that, if needed, can be very detailed and abstracted, but can also be implemented in a simple form when appropriate.[17]

The main problem with standards, however, is the difficulty in agreeing upon just one. Standards are like opinions, everyone has one or at least one they prefer. But standards will play a key role in the rate of advancement and ability to integrate data from air sensors. The format wars of VHS versus Betamax or DVD versus Blue-ray are testaments to both the promise and pitfalls of technology adoption and market penetration.

Practical Solutions

Given the needs at hand, organizations are now putting efforts into providing practical solutions for focused problems. The IBM Smart Cities Challenge for Louisville, KY, is one such effort. Despite the envious number of desirable rankings as a great place to live and do business,[18] Louisville also had a problem: air pollution and public health. It ranked second for most unhealthy days for asthma, ninth for annual particulate pollution, and things seemed to be trending the wrong way.[19] The city's topography and proximity to regional air pollution sources seemed to be adversely affecting the population and tarnishing its image. But this wasn't just an image problem with a marketing solution. Asthma has real economic consequences from productivity to healthcare costs to mortality. The challenge for IBM was to identify and analyze actionable data—including big data—to provide insights around the increasing level of asthma and the burden of this disorder in the community.[20]

Meeting the challenge required an initiative that not only implemented big data elements such as data mining, machine learning, and predictive modeling, but also required changes in governance (public–private partnerships) and community engagement (encouraging citizens to use mobile apps to collect and upload data).[21] While the outcomes are not yet clear, the potential benefit from the infusion of data that numerous air sensors could provide in determining spatio-temporal patterns of air pollution is intriguing. It also demonstrates the sort of comprehensive and systematic changes that are required to meet complex challenges.

Clearly, much careful thought and deliberation among stakeholders is required when we are confronting a future that might include the possibility a vast number of new air quality sensors of varying quality being deployed. Many of these new sensors are likely to be portable and also have GPS capabilities allowing for mobile collection and transmission of data. But questions remain regarding data quality and how these measurements can best be utilized given a variety of use cases. One suggested framework was that of a "generative platform" (i.e., one that invites contributions from anyone who cares to make them).[22] The contributions start among amateurs, who participate more for fun and whimsy than for profit. Their work, previously unnoticed in the mainstream, begins to catch on, and the power of the market kicks in to regularize their innovations and deploy them in the markets for larger than the amateurs' domain.[23]

One realization of the generative platform might be the development of concepts such as, "Open Air,"[24] which allows for a diversity of participants, from governments to individuals, using a variety of equipment, from reference grade stationary monitors to inexpensive mobile sensors, collecting on differing time and spatial scales. But even in such a utopian vision, the ways in which to integrate disparate data sets, where the data reside, the quality of the data, and who "owns" them, still remain critical and non-trivial questions.

Given that this is a rapidly evolving area of research and product development, growing pains are to be expected. The workshop attendees were clearly engaged and enthusiastic about the prospects that air sensors might, in the near future, provide air monitoring capabilities that are cheaper, faster, and more democraticized, allowing broader engagement of public in issues of environmental health. **em**

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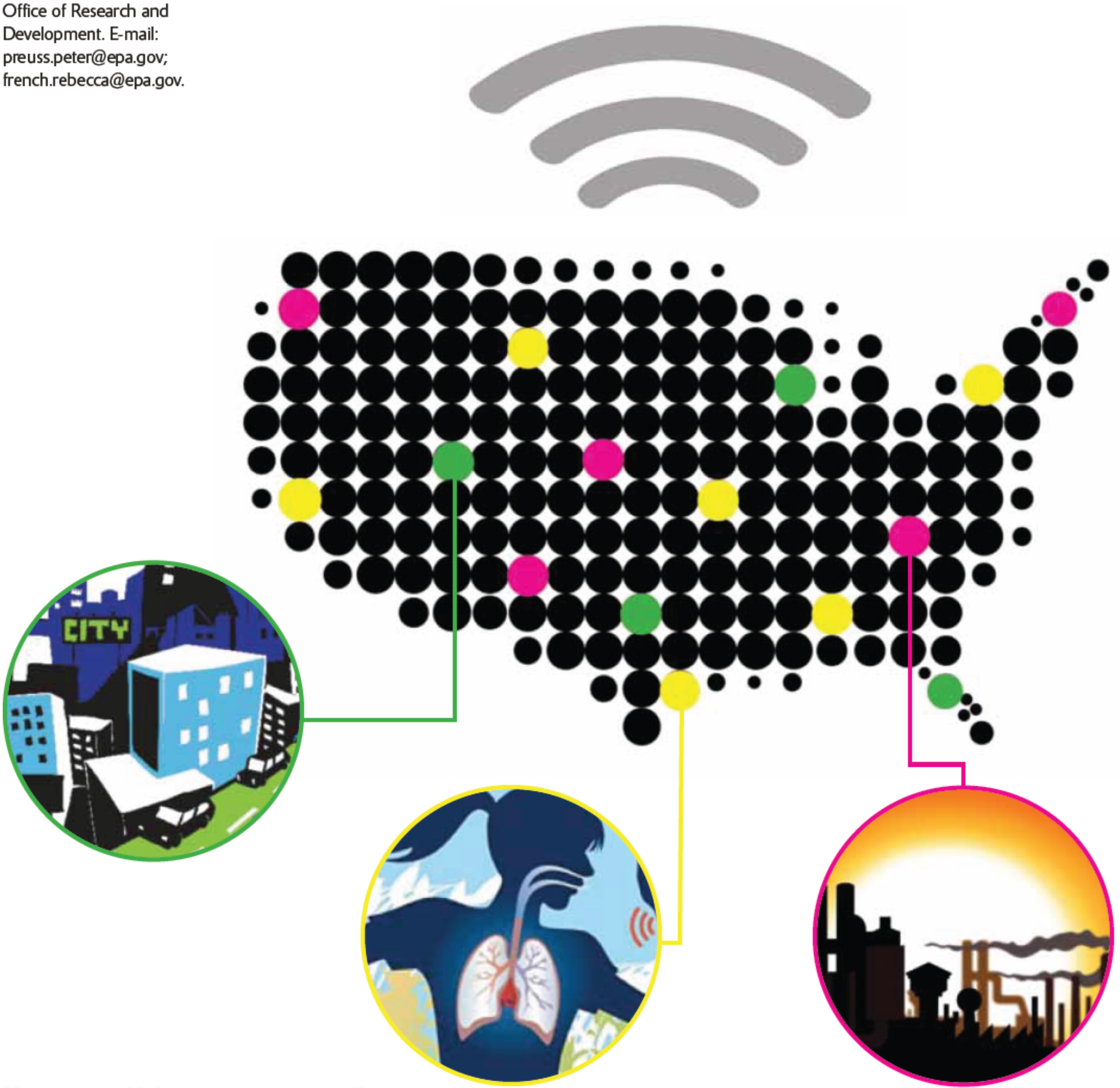
Disclaimer: The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development funded and managed the research described here. It has been subjected to agency's administrative review and approved for publication as an EPA document.

A Sensor World:

by Peter Preuss and Rebecca French

Peter Preuss is Chief Innovation Officer and **Rebecca French** is AAAS Science & Technology Policy Fellow, both with the U.S. Environmental Protection Agency's (EPA) Office of Research and Development. E-mail: preuss.peter@epa.gov; french.rebecca@epa.gov.

Rapid changes in technology are leading to a new generation of environmental monitoring instruments, software, and applications. The U.S. Environmental Protection Agency (EPA) has sought to build and grow the community of developers, researchers, and stakeholders interested in small, low-cost, user-friendly technology for air pollution. This article presents the vision for a world using low-cost sensors and how that may transform the status quo of air quality monitoring in the United States.



Next-Generation Air Monitoring At EPA

We will live in a sensor world. The Internet is becoming the internet of things—devices and apps that are connected, including many different types of sensors. Sensors are all around us, from our cars to our hospitals. This technology is becoming an increasingly important part of experiencing our environment. Rapid technological developments are leading to the production of small, low-cost air pollution sensors. Federal agencies are prime catalysts in helping to encourage this development. For example, the National Science Foundation has awarded an Engineering Research Center grant of $18.5 million to North Carolina State University and its partner universities to develop the next generation of self-powered health and environmental sensors.[1]

Similarly, the FP7, the European Union's Seventh Framework Programme for Research, has awarded a grant of nearly 12 million euros (16+ million U.S. dollars) to 30 research groups and companies from 20 European countries for CITI-SENSE.[2] CITI-SENSE focuses on citizen participation in environmental monitoring, decision-making, and planning. The research will develop, test, demonstrate and validate the use of portable low-cost microsensor packs with mobile phones for use in community-based environmental monitoring.

These new technologies and their use by academe, government, and the public will have large implications for the future of air quality monitoring.[3] Consider the following possibilities:

- in-plant sensor networks and fence-line monitors installed at facilities, allowing them to use sensor networks to detect and control fugitive emissions, preventing and reducing pollution;
- emissions monitored at the source and using that information to educate, engage, and empower environmental justice communities and partners;
- exposure data directly connected to personal and environmental health through the use of wearable sensors to engage citizens in personal monitoring; and
- a high-density sensor network of stationary and mobile sensor platforms to supplement current monitors providing real-time, local, and high-density data on air quality.

Sensors are also helping to solve a problem at the intersection of public policy and public finance—that is, that the federal government, states, and localities cannot continue to afford the expensive air quality monitors that we now use to measure pollutants in our environment. There is hope that the sensors now being developed could be a fraction of the cost of today's monitors that are in the $100,000 range, perhaps reducing the cost by a factor of 10, or even 100. In addition to lowering the overall cost of monitoring air pollution, such low-cost sensors will allow us to put sensors in many more places than we can currently afford. Subsequently, that information about the environment can be put in the hands of millions of people who, previously, have had no access to this information. With such a future at stake, EPA needs to be prepared to ride the bow wave and help develop this technology to meet a variety of environmental protection needs.

Next-Generation Air Monitoring

EPA is focusing on building a community of developers, users, state agencies, local communities, universities, and the private sector. EPA has worked on sensors across a broad spectrum of activities, including testing sensors, awarding Small Business Innovation Research (SBIR) grants, convening workshops, releasing a draft Next-Generation Air Monitoring Roadmap, improving science outreach to stakeholders, and using open source challenges. These activities have created a space for innovation, information, and communication, provided laboratory assistance that developers don't have available directly, and created research opportunities for scientists outside of EPA.

Testing and Developing Sensors

EPA's research laboratories are engaged in a variety of projects to test and evaluate new monitoring technologies, including:

- conducting laboratory and field evaluations of

- promising sensor technologies for measuring ozone, NO_2, PM, and VOCs;
- developing advanced monitoring technologies that can be deployed in vehicles to assess fugitive and area source emissions;
- assessing the use of infrared cameras for fugitive emissions detection and leak repair; and
- evaluating prototype monitors such as the Village Green,[4] a neighborhood-friendly park bench that doubles as an air quality monitoring station, with data streamed directly to an accessible Web site.

Small Business Innovation

EPA also sponsors the development and testing of new technologies through the Small Business Innovation Research Program (SBIR), which announces funding opportunities annually.[5] Recently, the SBIR awarded a grant to develop a real-time flare combustion efficiency monitor.

Workshops

To build and engage a community interested in new sensors and other technology for air pollution, EPA convened the Apps and Sensors for Air Pollution Monitoring Workshop in March 2012.[6] The workshop featured current work in technology development and community efforts, and highlighted specific needs, challenges, and potential solutions.[7] In March 2013, another workshop entitled, Air Sensors 2013: Data Quality & Applications,[8] focused on new technologies, recent applications, emerging issues such as evaluating sensors for data quality and calibration, management, analysis of big data, and emerging technologies in the field. Subsequent articles in this issue will address these topics in more detail.

Draft Roadmap

The Draft Roadmap[9] shares EPA's early thinking about how best to support the successful development and use of new monitoring technologies and serves as a framework for engaging other agencies and organizations in this effort. EPA drafted the roadmap to identify key actions to advance the development and use of new monitoring technologies for air pollution. The Draft Roadmap summarizes major findings from literature reviews, workshops, and discussions with experts about next-generation air monitoring, particularly sensor technology. It identifies pressing issues in need of EPA leadership and an ambitious set of priority objectives for EPA and its partners to address. Priorities include working with states and other partners to interpret the data from new technologies; setting reasonable expectations for use of different technologies; engaging communities

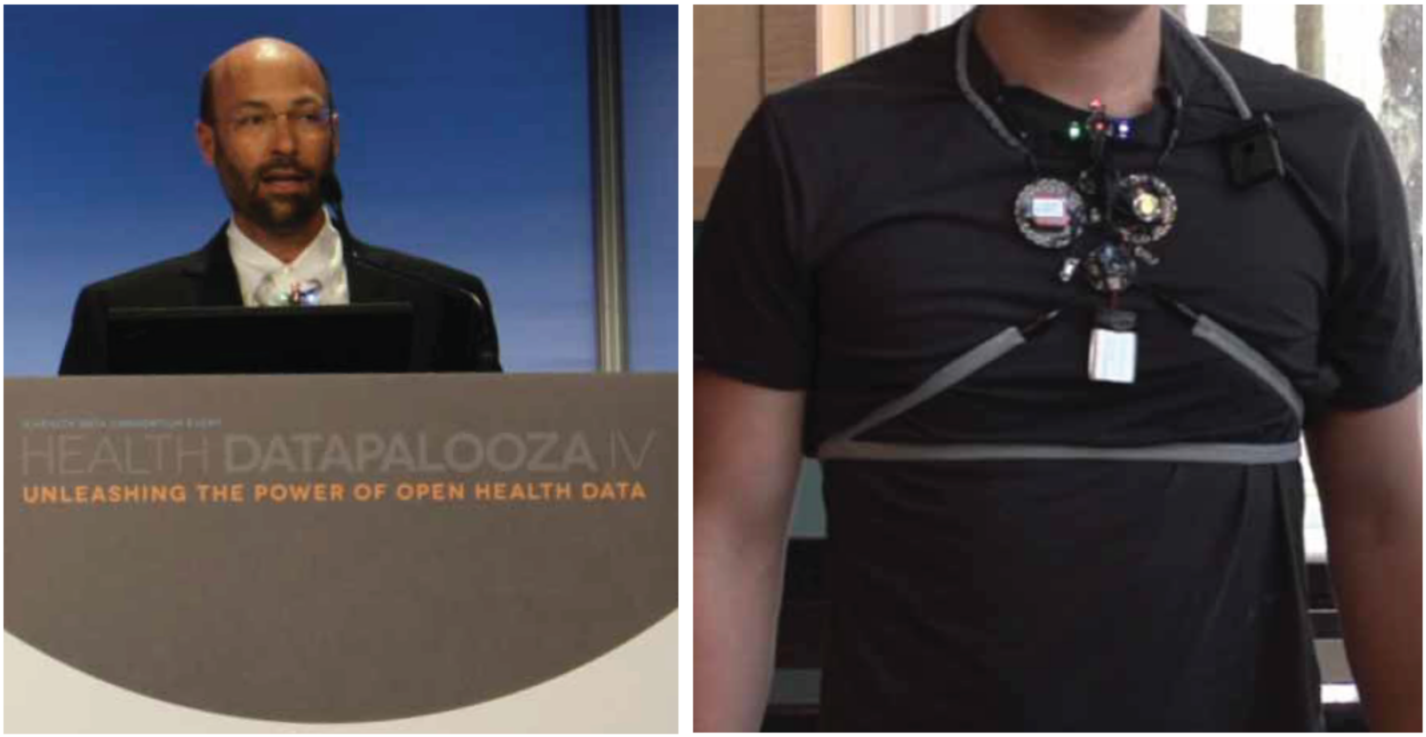


Figure 1. (left) David Kuller accepting the My Air, My Health Challenge award at the Health Datapalooza conference in June 2013. Kuller's company, Conscious Clothing, designed a sensor that integrates particulate matter and breathing rate and volume (right).

interested in using new technologies; responding to inquiries from concerned citizens; and preparing for managing large sets of data.

EPA Outreach

EPA scientists are reaching out to state agencies, community groups, citizen scientists, and others to provide relevant information on using new technologies for air quality monitoring. For example, the EPA Region 2 office has sponsored a series of Citizen Science Workshops.[10] In the workshops, EPA scientists discussed issues such as measurement uncertainty, quality assurance, and design of monitoring programs. These outreach efforts provide valuable technical information to community groups and others to improve the quality and utility of community-based monitoring data.

Open Source Challenges

EPA is exploring the use of open source challenges—describing a technical problem and inviting solutions from scientists all over the world. In 2012, EPA and the U.S. Department of Health and Human Services jointly announced an open challenge, My Air, My Health. It called on academics, industry researchers, and do-it-yourselfers to connect wearable air and health sensors, allowing citizens and communities to collect highly localized data, creating a meaningful picture of how the environment affects their well-being. Selected in June 2013, the overall winner was Conscious Clothing, with a prototype that integrates a wearable PM sensor with a stretchy fabric that can measure breathing rate and volume (see Figure 1).[11] Sensors like Conscious Clothing can also enable epidemiologists to assess the relationship between air pollution and public health in ways not possible before. Open source challenges have also generated ideas for benzene and acrolein sensors. EPA will continue sponsoring the challenges for high priority environmental problems.

Emerging Issues in Next-Generation Monitoring: Data

This article began with a vision for a world with ubiquitous sensors, but the sensors are only as

Table 1. Data Quality Objectives of the European Commission Air Quality Directive.

	O_3	SO_2, CO, $NO_2/NO/NO_x$	Benzene
Uncertainty for indicative measurements	**30%**	**25%**	**30%**

Notes: The Directives specify that indicative measurements must meet a Data Quality Objective that is about twice less stringent than reference measurements.

good as the data that they provide. Subsequent work in next-generation air monitoring at EPA might focus on the answering the following questions[12]:

- Who are the primary users of sensor data and how are they likely to use it?
- What are the applicable or appropriate data quality standards, legal standards, and/or best practices for different uses of sensor data?
- How can EPA support users in understanding the capabilities or characteristics of the new devices and software that generate the data?
- How might EPA and others make more air quality data available to the public?
- How should that data be presented to provide detailed, real-time, accessible, and understandable information to meet local users' needs?

The European Commission has begun to tackle these questions by issuing acceptable data uncertainty values for indicative measurements of air pollution[13] (see Table 1). EPA has not issued guidance for indicative measurements of air pollution.

The questions above are not limited to air quality. They should be considered for water quality measurements and pollution monitoring in other media as new sensors are developed in those areas. For example, the XPRIZE recently issued a new challenge to develop an inexpensive and easy-to-use sensor to measure acidity in the ocean.[14]

As you read the articles in this month's *EM*, you are invited to consider these questions for yourself, consider how you would answer them, and join the community of next-generation air monitoring.[15] **em**

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