Highlights from the Air Sensors 2014 Workshop

by Amanda Kaufman, Ron Williams, Sherri Hunt, Rebecca French, Holly Wilson, Gayle Hagler, Vasu Kilaru, Philip Fine, Stacey Katz, Gail Robarge, Dustin Renwick

The U.S. Environmental Protection Agency (EPA) hosted its fourth next-generation air monitoring (NGAM) workshop to discuss the current state of the science in air sensor technologies and their applications for environmental monitoring. This year's meeting, *Air Sensors 2014: A New Frontier*, was held in Research Triangle Park, N.C., June 9-10, and featured five sessions covering topics including new sensor technologies, community sensing, making sense of sensor data, sensor performance, and perspectives on the air sensors frontier. In excess of 500 onsite and internet-based registrants attended the workshop.

The workshop began with opening remarks from EPA Deputy Administrator Bob Perciasepe. He encouraged participants to leave with a better understanding of sensor technology, new ideas and new objectives. He emphasized using advances in technology and collaboration to foster citizen science and environmental justice projects. EPA's Strategic Plan outlines sustainability and community partnerships and this workshop supports these goals through participation, understanding, and problem solving.

Chet Wayland (US EPA) opened the meeting and introduced the goals for the workshop, to: enhance collaboration; inspire developers; learn about exciting new technologies; discuss approaches for citizen science; discuss data collection, interpretation, and management; define the state of the science for sensor performance; and share information about ongoing activities and opportunities. The following is a summary of the findings from each of the five sessions and two federal panel discussions.

Hot New Sensor Technologies

Sherri Hunt (US EPA) chaired this session that highlighted several new sensor technologies and their applications. Speakers in this session covered a range of topics, including smartphone spectropolarimeters, wearable physiological and environmental monitoring sensors, a wearable gas chromatograph, and methane and the sensor revolution.

Aerosols were highlighted as important pollutants to measure due to health, economic and climate implications. One novel technology showcased by Frans Snik (Leiden University, The Netherlands) was the iSPEX, a miniaturized sensor developed by astronomical instrumentation researchers in the Netherlands. The iSPEX is a smartphone accessory which utilizes an iPhone's camera to measure the spectrum and polarization of scattered light and estimate aerosol optical depth under clear sky conditions. Recently, thousands of citizens in the Netherlands volunteered to use the iSPEX, took measurements, and uploaded the data via the iSPEX app to a central database under a pilot initiative to identify pollution hot spots[1]. The iSPEX sensor has implications for both citizen science as well as validation and evaluation of satellite measurements of aerosol optical depth.

A consistent message throughout the session was the need for lower power draw to allow for longer and more practical uses. John Muth from the Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), NC State University, stated that the goal of the ASSIST group is to use nanotechnology and energy harvesting to power miniature, wearable, low-cost sensors for personal health and environmental monitoring. He also emphasized that microenvironments vary and sensors need to be created with this in mind. A better understanding of the correlation between human physiological response and environmental stressors is needed. Many academics across universities are working to develop sensors to address this need. Wearable volatile organic compound (VOC) personal exposure monitoring microsystems (PEMMs), developed by the Center for Wireless Integrated MicroSensing & Systems were discussed, as well. Next-generation VOC PEMMs will be designed for improved power efficiency, low mass, and new construction using alternative materials.

Steven Hamburg, Chief Scientist at the Environmental Defense Fund (EDF), discussed market-based solutions that drive innovation. He suggested the sensor revolution is allowing scientists to look at emissions of climate-warming pollutants. A particular focus emphasized was assessing methane, a greenhouse gas with high global-warming potential, using low cost sensors. Given the distributed nature of methane emissions and possible industrial leak reductions (e.g., pipelines, oil and gas well pads) that could be possible, expanded detection techniques for methane emissions may lead to major reductions in emissions. The EDF performed challenge tests using methane sensors near drilling platforms and found that a 60% reduction in methane emissions could be possible in 10% to 20% of the sites tested. The EDF's vision is to create cost-effective monitoring networks, faster leak detection and repair, and co-benefits for industry, public health and the environment.

Community Sensing – What's in my Air?

Rebecca French (AAAS at US EPA) and Holly Wilson (US EPA) chaired this session, which focused on community air quality sensing. Urban and rural communities from around the world were represented with a wide range of demographic variables and air quality concerns. A total of 87 educators, community action groups (CAGs), tribal governments, and similar community-based groups participated in the workshop through the oral plenary presentations and poster sessions.

Kris Ray, manager for the air quality program for the Confederated Tribes of the Colville Reservation in EPA Region 10 discussed a series of storms and large-scale forest burning events that led to high levels of air pollution and subsequent hospitalizations in the fall of 2013. They used $PM_{2.5}$ monitors to paint a picture of the pollution in the area, and they emphasized that portable monitors like sensors being discussed in the workshop would help these efforts.

[1] http://ispex.nl/en/

Professor Elizabeth Ablah (University of Kansas) created the Wichita Initiative to Renew the Environment (WIRE) project in Wichita, Kansas. Ablah discussed her experience with collecting air quality data and community partnerships. More than 1,500 participants, including neighborhood associations and middle school students, were involved in multiple projects. Through the Advancement via Individual Determination (AVID) project, students conducted research, created educational materials and brochures, wrote letters, and hosted a media event to educate their community about air pollution created by idling vehicles. Lessons learned from this project were that researchers need to talk to community members, for example, at town meetings and local community gatherings. Additionally, building on existing projects such as AVID or readily available data could be an alternative to new monitoring.

The South Ward Monitoring Project, a community air monitoring project in urban areas of New Jersey, aimed to educate students, identify hot spots and develop policy. Professor Nicky Sheats (Thomas Edison State College) shared that students learned about air pollution science, atmospheric chemistry, sensor technology, and environmental justice. A lesson learned from this project was that more time was needed for monitoring and subsequent classroom data analysis and projects. Future projects would focus on students giving presentations to policy makers.

Air monitoring projects in rural communities were also discussed. One such project included volunteers from a rural agricultural community in Delta County, Colorado, set out to prove that their air was polluted. The goal of their research was to conduct a pilot project with volunteers conducting science for a specific purpose. Local teachers used project-based learning to integrate citizen science into the classroom. The educational benefits of this type of project expanded to high school students, teachers, the local community, and the scientific community. Sarah Sauter, Executive Director of the Western Slope Conservation Center and Ben Graves, a teacher at Paonia High School, led the project. In his presentation, Graves said, “This is a great illustration of the idea – leaders, cultures, systems. We’re in the process of building leaders who can encourage a culture in which the systems we’re talking about can be applied. If you don’t have good leaders, you aren’t going to have success.”

Atsushi Yamamato, a researcher from HORIBA Instruments, Inc. in Japan, discussed the HORIBA smart phone enabled radiation monitor that was used by citizens following the 2012 Fukushima nuclear disaster. The monitor was created to be easy to operate, accurate, robust, and reliable. Using these monitors, citizens were able to gain firsthand knowledge of local conditions and provide data complementing government-based data collections. Future enhancements of the HORIBA monitor will include real-time mapping and data sharing.

Making Sense of Air Data: Applying Sensors, Sharing Data, and Interpreting Trends

Gayle Hagler and Vasu Kilaru (US EPA) chaired this session on making sense of air sensor data. The session comprised seven presentations during the course of two days. Presentations focused on a wide range of topics, including EPA’s perspective on sensor development, interpretation of air sensor data, application of low-cost sensors in field evaluations, sensor calibration and collocation, characterizing local air quality trends, using sensors to engage citizens and contribute to science, and facilitating data transfer from citizen-based monitoring efforts.

Kristen Benedict from EPA's Office of Air and Radiation (OAR) presented OAR's perspective on sensor development. She noted the multiple tiers of technology in the air monitoring landscape - historically, government-run air monitoring stations have been the primary data source and are operated under very strict protocols to meet regulatory requirements; meanwhile, new mid- and low-cost air monitoring systems are emerging with varying or unknown levels of data quality and long-term reliability. Benedict noted a variety of nonregulatory applications for emerging sensors, including informing network design, permitting, risk assessment, providing insight into near road concentrations, and fenceline monitoring. As an example of the benefits of new data sources, she noted the AirNow Satellite Data Processor Project (ASDP), which fuses satellite and monitoring $PM_{2.5}$ data. She stated that a key challenge for new sensor technologies is to ensure the device data quality is known and is sustained over its designated lifetime of use. In addition, appropriate ways to present sensor data is another emerging challenge. Participants were urged to understand that the Air Quality Index (AQI), which is based on health studies at longer time scales, was not intended to be used to compare with sensor readings, which are often made on much shorter time scales. Currently the health literature lacks sufficient information to address questions of the impacts of very short term (e.g. 1-minute) exposures. As a result, OAR is working to develop sensor messaging that could be used on a smartphone app that might help communities have a better understanding about such issues.

John Vandenberg from EPA's National Center for Environmental Assessment (NCEA) spoke of another challenge in interpreting new air sensor data—how data itself is not "information" – interpretation is required. This interpretation will be different for individuals, communities, state and local officials, and federal agencies. The Air Sensors Health Group (ASHG), comprising numerous federal researchers, was formed to help the State agencies, local agencies and EPA Regions provide answers to concerned citizens. In addition, they hope to help consumers understand how to interpret the readings from their sensors, and to help guide sensor developers to produce instruments with meaningful information or translation. Current challenges stem from the lack of short-term health effects studies -- which in turn leads to a lack of short-term health reference values for general population exposure, lack of comparability between short-term (e.g., 1 minute) sensor readings and National Ambient Air Quality Standards, and effective and appropriate communication.

Mike Bergin from Georgia Institute of Technology presented on applications of collocated low-cost sensors in field evaluations and multi-sensor approaches to derive emissions factors. He displayed data from collocated light-scattering PM and CO_2 sensors, as well as a mid-tier cost black carbon sensor. He presented results of a study in India comparing data from a higher cost beta-attenuation PM mass monitor (EBAM) compared to multiple low cost light-scattering particle sensors (Shinyei, Model PPD20V) and reported an R^2 value > 0.7; however, the concentration levels were in the range of ~20-200 $\mu g\ m^{-3}$. Conversely, another sensor type from the same manufacturer (PPD42NS) showed weak to no correlation against the EBAM instrument. The Georgia Tech research group also demonstrated estimating PM emission factors measured in situ next to an Atlanta freeway by coupling a Shinyei Model PPD20V particle sensor with a low cost non-dispersive infrared CO_2 sensor (COZIR). Lastly, Bergin emphasized the impact of citizen science and social media in Beijing. The Beijing state department installed a PM monitor that tweets the air quality level on Twitter. This method was more effective at engaging the pubic in environmental matters compared to publishing scientific papers. Other geographical areas and/or projects could benefit from using social media to disseminate information and foster interest in environmental citizen science projects.

Alexis Shusterman from the University of California, Berkeley discussed the Berkeley Atmospheric CO_2 Observation Network ($BEACO_2N$)[2], which consisted of 25 independent CO_2 nodes on museum and elementary school rooftops. The nodes also included sensors for O_3 (Alphasense), NO, NO_2, and CO (B4 sensor). They performed lab and field calibrations of the nodes and collocated them with reference instruments. The overarching goal of the project was to make a networked instrument greater than the sum of its parts. For example, under strong wind conditions with prevailing winds from the ocean, the entire sensor network may be assumed to be exposed to the same air concentrations for a period of time, which may allow for in situ pseudo-calibration of the sensor nodes to one another. Shusterman concluded with the questions of how to quantify statistical sensitivity benefits of a network sensor and how to best take advantage of the correlations between node readings.

Dane Westerdahl from the City University of Hong Kong (CityU) discussed low-cost sensor application development and testing to map outdoor air pollution in Hong Kong. Characterizing air quality in Hong Kong is complex due to mountainous island geography, high density urban population, numerous pollution sources (e.g., major roadways, port) in close proximity to population, and complex local meteorology. The CityU near-term research is focused on monitoring microenvironments of concern for exposure, such as traffic impacted areas using new CO_2 and $PM_{2.5}$ sensor systems. Preliminary laboratory testing revealed strong correlation for the CO_2 and $PM_{2.5}$ sensors against reference instruments. In addition, the CityU research team installed dispersive infrared absorption spectroscopy (DIRS) sensors to measure CO_2 in schools. Clear casings were used allowing children to see what was inside the box and learn about the technology. He noted that additional data on local air quality trends may inform the public and support government agencies in developing effective policies related to urban development and risk reduction.

Alena Bartonova from CITI-SENSE, EU[3] followed with a presentation on using sensors to engage citizens and contribute to science. The Citizens' Observatories were developed to empower citizens to contribute to and participate in environmental governance, support and influence community and policy priorities and associated decision making, and to contribute to the Global Earth Observation System of Systems (GEOSS)[4]. CITI-SENSE installed sensors in specific locations to study three environments: urban air, public spaces, and school indoor air. The sensors were all connected through the Citizens' Observatory, which was used as a sharing platform. Data fusion involved a combination of sensor data from CITI-SENSE with spatially distributed auxiliary information (i.e., statistical and deterministic models, regulatory observations). Data assimilation involved integration of sensor data from CITI-SENSE into a

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[2] http://beacon.berkeley.edu/
[3] http://www.citi-sense.eu/
[4] https://www.earthobservations.org/geoss.shtml

pollution dispersion model. Challenges to be met included the need for dialogue between data providers and users, conveying uncertainty in a user-friendly way, merging global and local observational information, merging observational and model information and their errors to gather added value information, and doing all this in a cost-effective manner.

The final presentation in this session was given by Alan Steremberg from Weather Underground[5]. He discussed the evolution of Weather Underground, the world's largest network of more than 36,000 personal weather stations. Upon merging with The Weather Channel, Weather Underground stored and backed up the history of weather stations and improved quality control. The Weather Underground network was created by leveraging enthusiastic citizens to monitor weather, building close relationships with hardware vendors, and facilitating data transfer. Steremberg went on to talk about the possible use of plug-and-play sensors. There is a need to add more pollution sensors to existing hardware. However, the problem with many weather stations is that they have fixed sensor configurations. He stated the solution is to create data architecture standards so different sensors can be aggregated into existing monitoring systems.

Sensor Performance – Lessons Learned from Field and Lab

Ron Williams (US EPA) chaired this session on sensor performance and lessons learned from the field and lab evaluations. He began the session by presenting findings on sensor performance characteristics testing that EPA conducted evaluating select low cost NO_2 and O_3 sensors. The subsequent sensor evaluation reports showed that most sensors had precision under 10 part per billion (ppb), which is highly desirable. In practice, one would like to see precision under 20%. The sensors responded quickly to changes in NO_2 and O_3 levels -- some in seconds, most in a few minutes. Many of the sensors were co-responsive to interfering pollutants (i.e., positive or negative measurement responses were caused by a substance other than the one being measured). Problems included sensors sometimes failing if they were challenged to adverse temperature or humidity conditions. Despite many sensors having the ability for Wi-Fi or cellphone connectivity, it was noted that wireless connectivity did not necessarily equate to ease of use. Another problem was the lack of data standards and meta data leads to variability of data formats for each instrument. However, creation of data standards has potential to address this issue. A second round of laboratory/field evaluations were recently completed involving PM and VOC monitors. The results of the NO_2 and O_3 sensor evaluations and a literature review are available on the EPA Next Generation Air Monitoring (NGAM) website[6].

A presentation by Michel Gerboles from the European Commission Joint Research Center focused on use and evaluation of low-cost sensors for monitoring of NO_2 and O_3 in ambient air. Sensors were tested in laboratory and field settings to determine if they met indicative measures defined in the European

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[5] http://www.wunderground.com/
[6] http://www.epa.gov/airscience/next-generation-air-measuring.htm

Legislation[7,8,9,10]. Findings showed that chemical sensors were often precise and stable over a long term (~180 days), but humidity interfered with their readings. Their tests often reported accuracy within a range of ±20% for a variety of sensor types. Resistive sensors had low interference and good sensitivity, but were hard to calibrate. However, it was possible to calibrate the sensors to adjust for model uncertainty using algorithms such as artificial neural networks.

Prior to presentations regarding lessons learned from field and lab evaluations, it was noted that there has been a shift in focus since the 2012 Air Sensors meeting[11]. The past meetings sometimes had discussions that sensors must have the ability to meet Federal Equivalent Methods (FEM) and people were feeling discouraged. Nicholas Masson from the University of Colorado stated that, "The current idea is to interpret, to start from the bottom and ask what problems can we solve with the data these sensors can produce? How can we use them? There is not a one size fits all solution." The benefits and drawbacks of laboratory versus field calibration were discussed, and then a model to fit the combination of data from the two types of calibration was proposed. Conclusions from initial discussions were that the researchers are still determining the length of time of collocation needed to produce a model that yields proper estimates.

John Saffell (Alphasense, Ltd.) began his presentation highlighting the sensor requirements he believed held the most weight (i.e., sensitivity, stability, and selectivity). He also warned the audience to always be aware of what smoothing has been done to the data shown in research studies. The Alphasense research focused on comparing sensor data from fixed sites versus mobile sensing. Lessons learned from their efforts indicated that the best results are achieved using a combination of fixed and mobile sites and that collocation is key to successful in-field calibration of mobile networks.

The final presentation in the session was by Natalia Mykhaylova from the University of Toronto. She stated that air pollution exposure is a multi-dimensional problem and that traditional exposure assessment is not enough to assess the health impacts of these mixtures. Temporal and spatial variation of pollution is greater than that of most air quality networks. She explained that sensor arrays are a promising solution due to their low cost, fast response, and availability for many pollutants. Her research group designed a device containing seventeen different pollutant sensors (e.g. O_3, NO_X, CO, CO_2, VOC) and collocated the devices with reference instruments for their targets. Field studies were conducted with baseline reduction to improve the identification of local polluting sources. By removing background data, they were able to begin to understand the quantitative impact of local sources at different sites.

Perspectives on the Air Sensors Frontier

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[7] http://nheerlpub.rtord.epa.gov/heasd/documents/CairClipNO2%20eval.pdf
[8] http://nheerlpub.rtord.epa.gov/heasd/documents/B4-O3%20aSense.pdf
[9] http://nheerlpub.rtord.epa.gov/heasd/documents/CairClipO3NO2.pdf
[10] http://nheerlpub.rtord.epa.gov/heasd/documents/protocol%20gas%20sensors.pdf
[11] https://sites.google.com/site/airsensors2014/background

Philip Fine, from the South Coast Air Quality Management District (SCAQMD), chaired this session focusing on the future of air sensors and perspectives on the direction in which sensor technology and research is heading. Topics included the consumer market for wearable sensors, the promise and peril of new sensor technology for air agencies and their partners, the European network of new sensing technologies, and new perspectives on monitoring air quality.

Steve LeBoeuf from Valencell, Inc. presented on the consumer market for wearable sensors, technological challenges, and opportunities for collaboration. He stated that consumers are the prime entry market, with devices such as the Nike+ and FitBit gaining popularity. Currently there are many proposals for wearable environmental sensors on crowdsourcing funding platforms, but according to LeBoeuf, it will be a long time before these sensors will produce high quality data.

Barbara Lee from the Northern Sonoma Air Pollution Control District presented on the promise and peril of new sensor technology for air agencies and their partners. The promises included increased availability of air quality data over a larger area at a lower cost, answers about localized air quality concerns, and more active and responsive engagement with the public about air quality issues. The perils mentioned were poor sensor design, improper use of sensors that could lead to bad data, challenges interpreting data, and lack of communication impeding deployment of good technology. The National Association of Clean Air Agencies views these as important issues and supports efforts to share information, evaluate emerging technologies, and engage agencies and communities. The take home message from this presentation was for citizens to reach out to state, local, and federal agencies for help on their projects.

Michele Penza from EUNetAir[12] presented on the European network of new sensing technologies for air pollution control and environmental sustainability. The main objective of the European Cooperation in Science and Technology (COST) Action TD110, EUNetAir, is to establish a pan-European research and development platform on the new sensing paradigm for air quality control. They created collaborative research teams, trained early stage researchers, and disseminated results on air quality control to industry, community, and policy makers, as well as the general public and high school students. The four COST Action TD1105 working groups include sensor materials and nanotechnologies; sensors, devices, and systems for air quality control; protocols and standardization methods; and environmental measurements and air pollution monitoring. The combined efforts of these groups are proposed to solve problems in the area of air quality control, environmental sustainability, indoor/outdoor energy efficiency, climate change monitoring, and health effects of air pollution.

The final speaker of this session, Prabal Dutta from University of Michigan, presented a different perspective on monitoring air quality. He presented statistics showing that on average Americans spend 87% of their time indoors, leading to the recommendation that the new frontier of air sensing should focus on the indoor environment. Following a personal account of using a household CO_2 monitor to conduct his own citizen science project, he stated that it would be ideal to correlate observations of

[12] http://www.eunetair.it/

devices a person is already wearing or using (i.e., FitBit) with that person's environment and collect the data in the cloud.

Federal Panels

Numerous federal agencies were represented during two federal panel sessions, including U.S. Department of Homeland Security (DHS), U.S. Department of Defense (DOD), U.S. Centers for Disease Control and Prevention (CDC), National Institute of Environmental Health Sciences (NIEHS), U.S. National Institute of Standards and Technology (NIST), U.S. Agency for International Development (USAID), and the National Aeronautics and Space Administration (NASA). The panels encouraged perspectives from each agency and allowed them to discuss their roles in using sensor technology, as well as to provide areas in which they would like to improve communication and collaboration with other agencies, institutions, and the general public. Examples of discussions include the following:

- Tony Esposito from the U. S. Department of Defense discussed next-generation chemical detection for safeguarding the United States from weapons of mass destruction.
- Gayle DeBord from the CDC provided examples of using sensors in occupational health safety settings[13].
- Mark Hoover from the CDC offered a table that described roles and responsibilities for sensor customers, creators, curators, and analysts. Roles and responsibilities included setting mission objectives, determining relevance, collecting data, validating data, storing data, sharing data, analyzing and modeling data, applying data, and determining effectiveness of the data.
- David Balshaw discussed sensor activities at the NIEHS. Their program aims to advance characterization of environmental exposures through improved exposure assessment at both the individual and population levels, define and disseminate the concept of the exposome[14], and to create tools, technologies, and the research capacity needed to characterize the exposome.
- Christa Hasenkopf from the USAID informed participants about the U.S. Global Development Lab at USAID and the Partnerships for Enhanced Engagement in Research (PEER) program that funds developing country scientists to conduct research in collaboration with U.S. agency scientists.
- Ethan McMahon from NASA presented on the International Space Apps Challenge[15] that encouraged smartphone app development for citizen science.

Conclusions from the Workshop

In his closing remarks, Dan Costa, National Program Director for EPA's Air, Climate, and Energy Research Program, stated that the extremely high degree of worldwide interest involving sensor technologies for

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[13] http://www.cdc.gov/niosh/topics/drst/
[14] http://www.cdc.gov/niosh/topics/exposome/
[15] https://2014.spaceappschallenge.org/

a wide variety of purposes bodes well for the field. The next steps will involve starting to link sensor data to health information to generate portfolios that could be used in public health settings as well as in community self-surveillance.

Based on the topics discussed throughout the conference, it was evident that several areas are still in need of development. Citizen science projects often are not fully established or executed due to various reasons, including lack of funding and lack of appropriate guidance on project design, technology use, and data interpretation. Data handling continues to be an issue, as well. Making data easier to share is a necessary step for technology development and future projects. Lastly, there is a need for systematic understanding of sensor viability. There is still not a definitive and consistent program or procedure by which sensors are evaluated.

Disclaimer:

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