The Changing Paradigm of Air Pollution Monitoring

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Abstract: The air pollution monitoring paradigm is rapidly changing due to recent advances in 1) the development of portable, lower-cost air pollution sensors reporting data in near-real time at a high-time resolution, 2) increased computational and visualization capabilities, and 3) wireless communication/infrastructure. It is possible that these advances can support traditional air quality monitoring by supplementing ambient air monitoring and enhancing compliance monitoring. Sensors are beginning to provide individuals and communities the tools needed to understand their environmental exposures with these data individual and community-based strategies can be developed to reduce pollution exposure as well as understand linkages to health indicators. Each of these areas as well as corresponding challenges (e.g., quality of data) and potential opportunities associated with development and implementation of air pollution sensors are discussed.

Abstract Figure

Picture of handheld air quality monitor taken with permission from Alan Mainwaring.

Historically, approaches for monitoring air pollution generally use expensive, complex, stationary equipment[1, 2], which limits who collects data, why data are collected, and how data are accessed. This paradigm is changing with the materialization of lower-cost, easy-to-use, portable air pollution monitors (sensors) that provide high-time resolution data in near real-time. These attributes provide opportunities to enhance a range of existing air pollution monitoring capabilities and perhaps provide avenues to new air monitoring applications. Sensors tied to advances in computing and communication also provide enhanced availability and accessibility of air monitoring data. Sensor devices are currently available to monitor a range of air pollutants and new devices are continually being introduced [3]. Meanwhile, the emergence of information on the high spatial variability of primary air pollutants[4-10] and per capita increase in asthma or other health conditions sensitive to air pollution[11] motivates finer-grained and more personalized air monitoring data collection. Indeed, the attraction towards lower cost sensors is sufficiently great that, even before sensor performance has been characterized, widespread data collection and data sharing using new sensors is already occurring (http://airqualityegg.com/). However, challenges remain regarding the use of sensors and sensor data, chiefly sensor data quality and derivation of meaningful information from data sets.

Current State of Sensor Science

The current paradigm change in air pollution monitoring is being catalyzed by recent advances in multiple areas of electrical engineering that include 1) microfabrication techniques; 2) micro-electro-mechanical system (MEMS) that can incorporate microfluidic, optical, and nanotube elements; 3) energy efficient radios and sensor circuits that have extremely low power consumption; and 4) advanced computing power suitable for handling extremely large databases (e.g., potentially many terabytes, 10^{12} bytes) and user friendly data visualization [3]. The use of sensors also are greatly increased due to the availability of wireless networks, allowing communications across widely dispersed sensor networks as well as web services (e.g., Xively, https://xively.com/) that allow for information access in near real-time across a broad spectrum of users. The combination of these advancements is helping to drive the development of small, lower-cost, mass-produced sensors.

Air pollution sensors can be separated into two main categories, those that measure the concentration of gas phase species and those that measure either particulate matter (PM) mass

concentrations or various properties of particles (e.g., scattering or absorption). All sensors systems consist of a few basic elements that include: 1) the sensor element that responds to the species of interest and varies with the pollutant mass in a given volume of sampled air; 2) the transducer that converts the responses to electrical signals; 3) data storage capability or a link to a communication device (e.g., microradio transmitter or cell phone); and 4) a source of power (e.g., battery or energy harvesting).

Most commercially available gas sensors are based on two main principles: 1) those that depend on interactions between the sensing material (electrochemical cell or metal oxide semiconductor) and gas phase component such as nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), and volatile organic compounds (VOC) and 2) those that measure absorption of light at visible (e.g., for O_3 and CO_2) or infrared wavelengths (e.g., CO_2), or by chemiluminescence (NO_2) (see examples, Tables 2 and 3). Particulate matter mass can be measured directly by changes in frequency of an oscillating sensor element[12] or indirectly based by light scattering using a proportionality constant that relates the scattered light to a defined (e.g., <2.5 μm) aerodynamic diameter [AD]) PM mass concentration[8]. Light scattering and absorption by particles are important particle properties that have direct relationships to visibility and climate change. Table 1 provides a brief summary of general characteristics for gas and particle sensors, whereas Tables 2 and 3 lists specifications for examples of commercially available sensors for CO, NO_2, O_3, PM mass, and particle scattering and absorption and gives specifications of a current fixed site monitor for comparison. Emerging sensors are listed for direct determination of mass concentration because commercially available sensors do not exist.

Information regarding new lower-cost sensor performance is only beginning to be available. Recent studies have demonstrated promising performance for some lower-cost O_3 and NO_2 sensors[13-15]. However, the performance of most of the lower-cost sensors is not characterized and their long-term reliability of is unknown.

While not all monitoring objectives [e.g., National Ambient Air Quality Standards (NAAQS) compliance monitoring] can be met with current air pollution sensor technologies, some monitoring objectives can or likely will be achievable in the near future given that sensor packages with acceptable performance for a given application are being developed[13, 15]. For this to occur, the data quality must be suitable for the intended application(s). A specific example of

how the required data quality can vary depending on the application is easily illustrated with the pollutant CO. For automated methods used in regulatory monitoring, an accuracy of 7-21%, as estimated based on the maximum discrepancy specification outlined for the range of test concentrations in the Code of Federal Register 40 Part 53[16], is required. However, CO monitors typically used in homes, to alert occupants at approximately the 4-hour Acute Exposure Guideline Level, have accuracies ranging from ±20-30%[17]. It is also important to note that for many of the monitoring objectives, it is not critical to have sensors that meet uncertainty requirements of larger more robust monitors but to 1) know their uncertainty and other performance specifications, 2) be able to reference them to the more robust monitors, and 3) deploy a large number so that confidence in the measurement is improved due to many measurements rather than a few.

Examples of how sensor technologies might be used in air quality management activities include: (1) supplementing routine ambient air monitoring networks, (2) expanding the conversations with communities, (3) enhancing source compliance monitoring, and (4) monitoring personal exposures. These potential application opportunities are outlined below followed by associated challenges and approaches for solutions.

Supplementing Routine Ambient Air Monitoring Networks

Ambient air monitoring networks in the US currently measure air pollutants that include: 1) those regulated under EPA's NAAQS (http://www.epa.gov/air/criteria.html), 2) the chemical components of fine PM (http://www.epa.gov/ttn/amtic/speciepg.html), and 3) hazardous air pollutants (HAPs; e.g., benzene, toluene, and xylene; http://www.epa.gov/ttn/atw/allabout.html). Pollutants directly emitted into the air (e.g., CO, NO, NO_2, and certain chemical components of fine and coarse PM) have much higher spatial and temporal variability as compared to secondary pollutants that are formed in air (e.g., ozone and particulate sulfate) [4, 8]. Near sources, such as those immediately downwind of or adjacent to major roads, the concentrations of certain pollutants regulated under NAAQS (e.g., NO_2, CO), HAPs, ultrafine particles (UFPs, < 0.1 μm), and BC concentrations can vary significantly within only tens to hundreds of meters from the roadway [5-7, 9, 10].

Current US regulatory NAAQS requirements require use of a narrow range of monitoring technologies [Federal Reference or Federal Equivalent Methods (FRM or FEM)][16, 18], which are generally expensive to utilize in a dense monitoring network, especially when including infrastructure (electrical power, platform, security) and personnel requirements. Augmenting regulatory networks using portable, lower-cost air pollution sensors that report high-time resolution data in near real-time has the potential to provide improved estimates of the spatial and temporal variability of air pollutants; support ambient modeling, exposure, and health effects studies; and provide immediate access of information to the general public. However, current (including commercially available sensors) and emerging sensors need to be thoroughly evaluated to ensure that their performance specifications (precision, accuracy, sensitivity, interferences, etc) meet designated monitoring objectives. Few single or multiple sensor comparisons relative to historical or reference methods have occurred to date[13-15, 19]. In fact, no lower cost (e.g., < $2 K) sensor systems are designated as FRM or FEM, although a few have been compared to FEMs and in some cases appear to be comparable for NO_2 and O_3 (± 10%) [19]. Performance capabilities for commercially available sensors are provided typically by the manufacturer and a few selected sensors are listed in Tables 2 and 3 along with a FRM, FEM, or historical reference method for comparison. Sensors could be especially important for the measurement of HAPs and PM since samples are currently collected in the field over relatively long sampling times (e.g., hours to 24-hrs, respectively) with sample analysis in a laboratory at a later date. For these pollutants, data may not be available for up to a month or more.

Recent efforts in the U.S. to expand monitoring of NO_2 near-roads has led EPA to establish recommendations for proper use of the non-FEM commercially available "small, lightweight, and portable" NO_2 monitors [20]. Recommendations for use of these monitors include: co-location with a FEM or another similar monitor, and rotating the location of monitors (to evaluate bias of the individual monitors).

Expanding the Conversation with Communities and Citizens

Lower-cost and easy-to-use air pollution sensors provide citizens and communities with opportunities to monitor the local air quality that can directly impact their daily lives (see for example, www.citi-sense.eu). As they gather this information, they become more educated and informed about air quality in their community, which allows them to become more conversant on

potential air quality issues and better positions them to develop community-based strategies to reduce air pollution exposures to protect their health. This is part of a growing concept referred to as citizen science – "*…engage the public in making observations and collecting and recording data*;"[21]. While the concept of citizen science is not new [22], the movement has been growing due to the internet and the use of handheld devices such as cell phones with cameras [23, 24]. Citizen science activities take advantage of community-based participatory monitoring and "*crowd sourcing*" where many individuals voluntarily collect large amounts of data that is compiled and analyzed. For example, the Citizen Weather Observer Program collects weather data from personal weather stations, purchased by citizens across the US, and reports this data in real time to NOAA's Meteorological Assimilation Data Ingest System (http://www.wxqa.com/index.html). Already assembled personal weather stations are available for around 100 dollars (http://www.acurite.com/all.html).

Participatory monitoring is already occurring with air pollution sensors where they are being used in artistic demonstrations (http://f-l-o-a-t.com/), to stream data collected in a lower-cost sensor station location to a website (http://airqualityegg.com/), and to support crowd-sourced measurements while walking in an urban setting(http://aircasting.org/). While current data viewable on the web from many of these systems is suspect (e.g., large negative readings) or qualitative in nature, these activities demonstrate the interest and potential for citizen scientists to increase air monitoring data collection. Participatory monitoring is also occurring on the community scale in Durham, North Carolina where EPA, under its Village Green project [25], has deployed relatively low cost sensor technologies, that are self-powered with wireless data communication, in a platform designed for public settings (Figure 1).

Enhancing Source Compliance Monitoring

Air pollution sensors can be used for compliance monitoring of sources, both at the source location, and at the facility fence line as well as helping industries monitor emissions, reduce product loss, and enhance worker safety[26]. Specifically, as the performance of sensors improves and their costs drop, in-plant sensor networks should be able to detect and mitigate fugitive emissions (leaks) within facilities. This concept has been proposed for use in natural gas pipeline monitoring and in other oil and gas production and transportation facilities [27] . Sensors

also might be placed on existing mobile platforms, which are associated with facility operations and driven directly adjacent to sources. As these platforms move, data are collected and transmitted to plant operators providing near real-time surveillance opportunities to identify leaks. In-plant, fence line, and mobile platforms all provide opportunities for industry to reduce emissions, overall operating costs, and enhance worker safety.

Monitoring Personal Exposures

Personal exposure to air pollution is a critical link between ambient air pollution and human health effects. However, estimating personal exposures and attributing exposure to sources presents significant challenges because of the spatial and temporal variability of pollutants and difficulty in estimating the time individuals spend in different types of microenvironments (e.g., commuting in traffic, cooking indoors). The 2012 National Academy of Sciences (NAS) report *Exposure Science in the 21st Century: A Vision and Strategy* identifies ubiquitous sensors as one of the technologies that will likely substantially enhance exposure science and provide more accurate and comprehensive personal exposure data. A more complete understanding of personal exposure to air pollution will support the development and implementation of air quality management policies. For example, improving estimates of personal exposure may enhance environmental epidemiology studies (which often rely on limited ambient air monitoring data as inputs) that contribute to the scientific basis for NAAQS[28].

Additionally, when air pollution sensors are coupled with physiological sensors and location (GPS), a stronger connection can be made between a person's exposure environment and health indicators (e.g., heart rate, blood oxygen levels) and this has been demonstrated in research studies[29-31]. The connection between pollutant exposure and personal health indicators may allow healthcare providers to track these paired measurements and improve air pollution related diagnoses and treatment of medical conditions on a more individualized basis. The exposure biology program at the National Institute of Environmental Health and Sciences (NIEHS) is making an effort to better understand this connection by developing tools to connect more precise measures of personal exposure to markers of biological response [32] .

Challenges

The above discussion describes the current landscape for air pollution sensors and a likely range of opportunities for the application of sensors from enhancing our national air monitoring networks to community and individual monitoring as well as how sensors might be applied within and around sources to identify and mitigate emissions from industrial sources. However, there remain a number of across-the-board technical and practical challenges associated with this emerging area of science including: development of robust sensors that produce high quality data, rigorous evaluations of sensors, integration of data from multiple sensors of different quality obtained through multiple sources (e.g., government and citizen), and visualization and use of sensor data by the public and by agencies responsible for protecting human health.

Data quality is a key issue since data of poor or unknown quality is less useful than no data since it can lead to wrong decisions. Figure 2 illustrates relative data quality required for the potential applications outlined above. Work conducted at EPA indicates that many commercially available sensors have not been challenged rigorously under ambient conditions, including both typical concentrations and environmental factors[15]. Furthermore, even if sensors are well characterized, performance criteria have not been developed in the U.S., regardless of the anticipated sensor use, outside of the FEM criteria. However, using the FEM criteria, which requires data of high quality for purposes of monitoring compliance with the NAAQS (40 CFR Part 53), would likely be too restrictive for many sensor applications.

Commercially available sensors are lacking for PM and hazardous air pollutants. Specifically, there are no commercially available direct-reading PM mass sensors although they are under development [12] and surrogates for PM mass exist based on light scattering [33]. Additionally, a complete lack of commercially available chemical speciation PM sensors, with the exception of a handheld device that measures light absorption on sample collected on a filter, which is a relative surrogate for black carbon [34]. Few sensors are available for detecting specific HAPs and those that exist have often not been tested rigorously with complex mixtures of similar HAPs. While data storage has become more accessible, data governance (assessing, managing, using, improving, monitoring, and maintenance), processing, and visualization are major challenges that still require considerable effort [35]. As a part of the management and use of these data, the descriptive information associated with the collected data, called metadata, are also required but frequently not collected.

Communicating how air pollution measurements taken using sensors relate to health impacts is a significant challenge for sensor applications where the general public collects data. Air pollution health impacts result from both the level and duration of exposure, therefore national standards and chemical health benchmarks reflect both of these aspects of exposure. The level of the concentration recorded by an air pollution sensor at a specific point in time may be above or below a standard or health benchmark, but it may not reflect the duration of exposure related to that standard or benchmark (e.g., a standard that is based on daily or annual average exposures). As a result, communication, outreach, and educational materials are needed to provide guidance on how to place the sensor measurement in the appropriate context related to national standards and health benchmarks.

Opportunities for Solutions: A Changing Role for Government

To overcome data quality, data interpretation, and communication challenges, Federal, state, and local air quality agencies (including public health organizations) must provide guidance and advice on sensor use and data interpretation. The EPA is working to facilitate, communicate, and promote the responsible use of air pollution sensor data. This will help ensure air quality agencies, public health organizations, communities, and individuals may effectively take advantage of this new source of air quality data.

Toward that end, EPA has conducted a series of workshops[36, 37] and has developed a draft roadmap[38] to share EPA's early thinking about how best to support the development and use of new monitoring technologies. This roadmap summarizes findings from literature reviews and identifies recommendations and gaps to be addressed organized around three areas: (1) technology development, testing and integration, (2) technology demonstration, outreach, and communication strategies, and (3) IT infrastructure and new data streams.

The recommendations/gaps are beyond what EPA can address alone, but the roadmap provides a framework from which EPA plans to engage other agencies and organizations in collaborative activities. For example, EPA is planning to work with public health organizations at the federal and state level to expand on health messages associated with exposure to air pollution as currently done under its AirNOW program [39]. The Agency is also evaluating lower-cost sensors for criteria pollutants (NO_2, ozone, PM, and VOCs) in collaboration with sensor developers[15] and

federal and state partners and is developing data visualization methods, to support its Geospatial Measurements of Air Pollution Program, that could potentially be used to visualize mobile sensor data[40]. Other goals include: expanding the role of air pollution sensors in citizen science and working with regulated industries to facilitate the adoption of sensor technologies within facilities, at the fence line, and through mobile platforms that can help identify and mitigate emissions.

Advances in air pollution sensors are also part of EPA's new E-Enterprise for the Environment Initiative. This is a joint initiative among State agencies and EPA to improve environmental outcomes and dramatically enhance service to the regulated community and public. This is achieved by maximizing the use of advanced monitoring and information technologies, optimizing operations, and increasing public transparency. High quality mobile air pollution sensors coupled with internet technology will greatly expand the amount of information that EPA, states, industry, and the public will have to understand, reduce, and prevent air pollution. In addition, sensor technologies may also reduce the cost of compliance for regulated community. E-Enterprise will provide the infrastructure for accessing and sharing this information among all parties and for integrating this information with other relevant information, such as official air quality monitoring data, individual compliance data, and other data, such as the Toxic Releases Inventory.

The driver behind these efforts is that the use of these sensors can potentially lead to better protection of public health and the environment by providing communities with better data on pollution in their neighborhoods, helping regulated entities better manage their facilities, and reducing the costs of air pollution monitoring for public agencies, regulated entities and researchers. The changing paradigm for air pollution monitoring comes at an opportune time when Federal, State, and local air quality management organizations are working to maintain existing monitoring programs and meet new monitoring challenges while facing resource constraints. While this changing paradigm presents Federal, State, and local air quality and public health organizations with new challenges, these organizations should embrace this change because along with these challenges comes tremendous opportunities to improve air quality management and public health activities in the U.S..

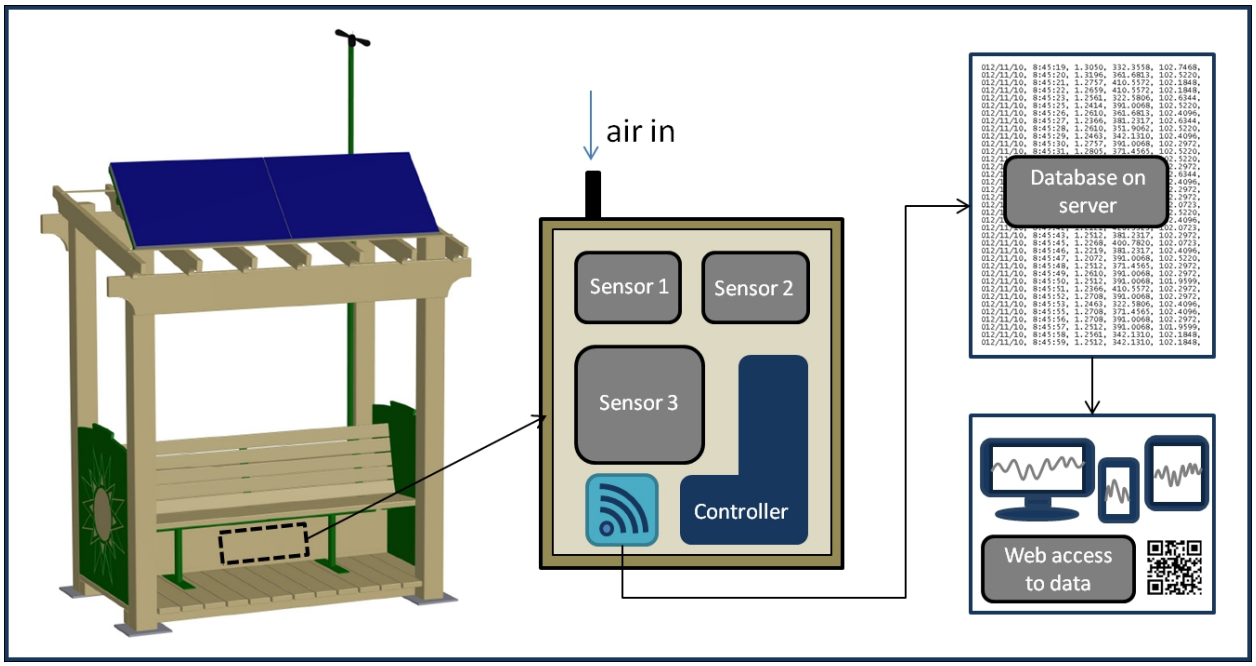

Figure 1. Example of a new paradigm for air monitoring – the Village Green Project system is solar-powered, suitable for public spaces, low maintenance, and wirelessly streams real-time data.

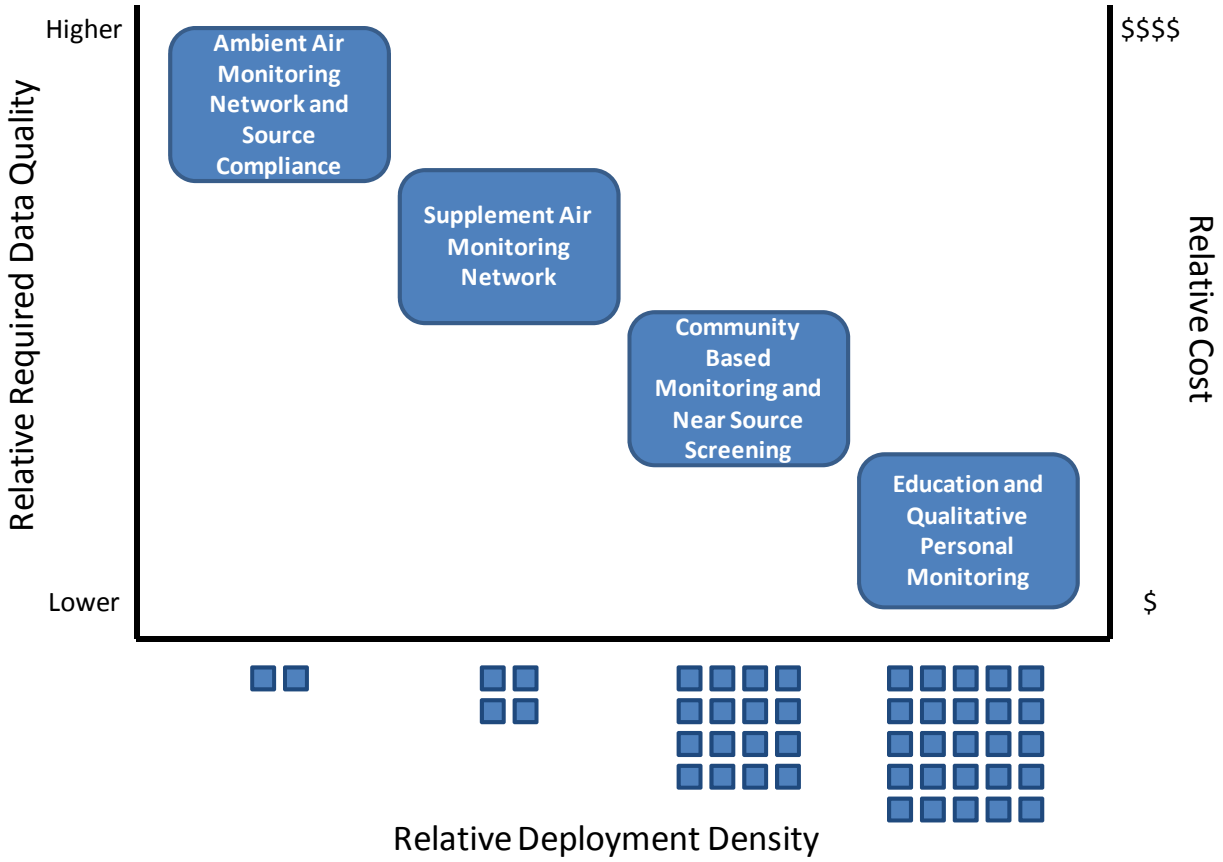

Figure 2. Relative data quality requirements, deployment density, and cost by application.

Table 1. Characteristics of gas and PM sensors. (adapted from Table S1[3] with permission, White R., University of California, Berkeley.).

Gases	**Strengths**	**Concern 1**	**Concern 2**	**Concern 3**
Electrochemical cell (EC)				
CO, O_3, NOx	Low cost, low power, small, real-time; more sensitive than MOS (metal-oxide-semiconductor) sensors	Interferences: CO, VOC, NO_2	Drift, frequent recalibration needed, 1 yr lifetime	
Metal oxide semiconductor (MOS)				
CO, O_3, NOx	Small size; stable, 1-2 yr lifetime, inexpensive	Sensitive to change of RH, T, P; cross-sensitivity	Power consumption; fragile materials	Typically less sensitive than EC
Non-dispersive infrared absorption (4.26 μm)				
CO_2	Compact, stable to changing RH and T	Sensitivity depends on path length	Calibration may be misinterpreted or inaccurate	Some single beam devices auto-calibrate as if background CO_2 is 400 ppb
Ultraviolet absorption (254 nm)				
O_3	Accuracy, stable to change in P	Size (not yet miniaturized)	Sensitive to changes in relative humidity	Cost
Particle Properties[a]				
Light Scattering	Small, inexpensive, commercially available	Not a direct mass measurement	Does not measure ultrafine particles	
Light	Handheld well established,	Still relatively large and	Requires changing a	

Absorption	stable, continuous	costly	filter	
Direct Particle Mass	Small, inexpensive, direct mass concentration; FBAR, QCM	In development stage	Likely sensitive to changes in T and RH	

[a]Most particle sensors still require independent evaluation under a range of ambient and indoor environmental conditions.

Table 2. Examples of commercially available portable, low-cost gas phase air pollution sensors that report high-time resolution data in near real-time for several NAAQS pollutants. Performance capabilities are from manufacturers' datasheets. Values after pollutant name in section headings refers to current US NAAQS (40 CRF 50) as a reference to ambient. The first row in each pollutant category (bold type) represents a typical fixed-site higher-cost monitor for comparison purposes only. Adapted from Table S2[3], with permission, White R., University of California, Berkeley. Sensor weights, shown in table below, are with battery unless indicated by an *.

Analyzer[a]	Sensor Technology	Range[b, c]	Accuracy[b]	Precision[b]	Environmental Limits[b]	Weight (kg)	Response Time (s)[b]	Price USD[d]
CO (8 h: 9 ppm; 1 h: 35 ppm)[d]								
TECO Model 48C	**IR absorption**	**0.3-100 ppm[1]**	**±1 %**	**0.1 ppm**	**5 to 45 °C**	**22.2**	**60**	**12K**
Langan DataBear, l T15d	Electrochemical Cell	2–200 ppm	0.5 ppm	0.5 ppm	23 to 40 °C	0.43	≥ 1	1.5K
Aeroqual Series 500[4]	Metal Oxide Semiconductor (MOS)	2-100 ppm	<±2 from 0-20 ppm; <±10% from 20-100 ppm	0.1 ppm	0-40 °C, 5 to 95% RH	< 0.46	< 150	1.5K
NO_2 (1 h: 100 ppb; annual average: 53 ppb)								

API, Model 200EM	**Chemiluminescence**	**0.05-1 ppm[3]**	**5%**	**5%**	**5 to 40 °C**	**27.0**	**20**	**8-14K**
Alphasense D-4 mini	Electrochemical Cell	0.2-20 ppm	±100 ppb	8%	-20 to 50 °C, 15-90% RH	Sensor only	<35	125 [4]
Aeroqual Series 500[5]	MOS	0.01-200 ppm	<±0.01 from 0-0.1 ppm; <±10% from 0.1-0.2 ppm	1 ppb	0 to 40 °C, 30 to 70% RH	< 0.46	<180	2K
O_3 (8 h: 75 ppb)								
API, Model 400	**UV absorption**	**<0.6 to 200 ppb**	**better than 1%**	**1 ppb**	**10 to 90% RH, 5-40 °C**	**12.7**	**< 20**	**8-14K**
2B Technologies, 202; FEM EQOA-0410-190	UV absorption	1.5 ppb to 250 ppm	1.5 ppb or 2%	0.1 ppb	0 to 50 °C	0.70*	10	5K
Aeroqual Series 500L[5]	MOS	8-500 ppb	8 ppb	1 ppb	-5 to 50 °C, 5 to 95% RH	< 0.46	< 60	2K
OMC-1108	Electrochemical Cell	0.01 to 10 ppm	±10%	10 ppb	0 to 40 °C, 0 to 80% RH	0.5	< 70	1.2K

[a]The first row in each section: characteristics of and performance of instruments typical fixed-site monitor, although others could have been chosen; [b]from manufacturers' datasheets. [c]The lower limit is estimated as LOD or 3 times the precision. [d]Current NAAQS in the US as a reference to ambient. [d]Price for sensor system as of May 2013. [1]User selectable from 1 to 10,000 ppm, [2]User selectable from 1000 to 20,000 ppm; [3]User selectable from 1 to 200 ppm. [4]Cost includes on the sensor component and not a complete sensor unit signal processing, storage, and/or communication; . [5]The Aeroqual S500 has swappable heads for different gases.

Table 3. Example of commercially available and emerging sensors for continuous measurements of PM mass and physical properties. Performance capabilities are from manufacturers' datasheets except where noted with a **. Text in bold type represents a typical fixed-site higher-cost monitor for comparison purposes only to the sensors that follow in that category. Emerging sensors are not commercially available. Adapted from Table S3[3], with permission, White R., University of California, Berkeley.

Reference Sampler / Sensor	Measurement Principle	Manufacturer	Accuracy	Precision	Limit of Detection ($\mu g/m^3$) or Lower Particle Size Detected (µm)	More Information** Weight (kg) and ~Cost ($, when available) as of May 2013
Direct determination of mass concentration						
FDMS-TEOM 1405-F	**Oscillating microbalance; Filter dynamics measurement system**	**Thermo Scientific**	**±0.75%**	**±2.0 $\mu g/m^3$ (1-h avg), ±1.0 $\mu g/m^3$ (24-h avg)**	**0.06 $\mu g/m^3$ (1-h avg)[c]**	**Measures volatile and non-volatile PM mass; Measurement range: up to 10^6 $\mu g/m^3$, 34 kg; $24,600 with PM10 inlet and PM2.5 cyclone**
QCM**	Impaction on piezoelectric sensors	UC Berkeley; [12]	±0.75%[d]	<10%[d]	-[b]	Quartz crystal microbalance; mass size distribution
MEMS-PM**	MEMS virtual impactor with FBAR	UC Berkeley; [12]	-[b]	-[b]	-[b]	Film bulk acoustic resonator; under development, sensor only
Indirect determination of mass concentration[a] and physical properties						

SMPS 3936	**SMPS: electrical mobility; Size distribution**	**TSI Inc**	**Size**: <3.5% Conc**: ±10% at <5×10^4 pt/mL, ±20% at <10^7 pt/mL**	**-[b]**	**2.5 nm**	**Number size distribution (e.g., SMPS 3936; size range 2.5 – 10^3 nm; max conc 10^8 pt/mL; 33 kg, $[b] (cost depends on model)**
MiniDISC	Diffusion size classifier, two electrometer stages; Ultrafine particle counter	Matter-Aerosol	±30%	-[b]	10 nm	Size range 10 to about 700 nm (modal value should be <300 nm); ~10^3-~10^6 pt/mL; 0.7 kg; $13,600
PM SHARP, Model 5030	**Light scattering*; Mass concentration**	**Thermo Scientific**	**±5% compared to FRM**	**±0.5 µg/m^3**	**-[b]**	***Continuously calibrated to mass against a beta attenuation monitor; Precision (2-σ, 86.4x10^3-s time resolution): Conc range 0-1000 µg/m^3; kg[b]; $22K with PM10 inlet**
831 Aerosol Mass Monitor	Light scattering; Mass concentration	MetOne Instruments	±10% to calibration aerosol	-[b]	0.5 µm	Range: 0-1,000 µg/m^3; 0.8 kg; <$2,000
Personal DataRAM, Model pDR-1500	Light Scattering; Mass concentration	Thermo Scientific	±5% of reading ± precision	±0.2% of reading or ±0.5 µg/m^3 60-s avg	0.1 µm	Size Range: 0.1–10 µm; Conc Range: 1 to 4x10^5 µg/m^3 Precision (2σ); 10-s avg; 1.2 kg; $5500 with PM2.5 and PM10 cyclones

Environmental Particle Counter, Model 3783	**Particle growth, light scattering; particle counter**	**TSI Inc**	**±10% at 10^6 pt/mL****	-[b]	**7 nm**	**Max conc: up to 10^6 pt/mL; Size range 7-3x10^3 nm; 10 kg; $[b]**
Handheld CPC, Model 3007	Particle growth, light scattering; Ultrafine particle counter	TSI Inc	±20% pt/mL**	-[b]	10 nm	Conc range up to 10^5 pt/mL; Size range up to ~1 µm; 1.7 kg; $[b]
DC1100 Air Quality Monitor	Light scattering; Laser particle counter	Dylos Corp.	-[b]	±15%, collocated**	0.5 µm	Size ranges: Pro: >0.5 µm, >2.5 µm or Household: >1 µm, >5 µm, difference between size ranges equals reported counts; Linear up to ~10^6 pt/mL with <10% coincidence**; ~0.4 kg;< $300
Aethalometer® Models AE22	**Light absorption, 880 nm used to estimate black carbon**	**Magee Scientific Corporation**	**f(uncertainty in flow rate); no standard for comparison**	**-[b]**	**<0.1 µg BC/m^3, 5 Lpm, 1-h avg****	**Several models and specifications vary by model; 18 kg; <$26K depending on model**
microAeth® Model AE51	Light absorption, 880 nm	AethLabs; Black Carbon	no standard for comparison	±0.1 µg BC/m^3 60-s avg**	<0.16 µg/m^3, 2.5 mL/s, 60-s avg	Precision at 2.5 mL/s flow rate; Range: 1-1000 µg BC/m^3 Resolution 1 ng BC/m^3; 0.3 kg; $6,000

[a]Conversion from light scattering, particle number or size distribution, requires estimates of particle density and shape factors; [b]No data.

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