Sensors and ‘Apps’ for Community-Based Atmospheric Monitoring

Recent advances in both sensors and wireless communication provide opportunities for improved exposure assessment and increasing community involvement in reducing levels of human exposure to airborne contaminants. These new technologies can enhance data collection to answer science and policy questions related to the health and environmental effects of air pollution.¹

by Richard M. White, Igor Paprotny, Frederick Doering, Wayne E. Cascio, Paul A. Solomon, and Lara A. Gundel

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In recent years, wireless sensor networks (WSNs) have matured and greatly lowered the cost of collecting data by eliminating the wiring that was once necessary. A 2010 U.S. Department of Energy cost-benefit analysis of changing from wired to wireless automation systems indicated a three-fold reduction in the initial investment and a five-fold reduction in annual operating costs. In this article, we describe a particulate matter (PM) monitor made by microfabrication techniques, derived from the manufacture of integrated circuits, and show how sensor data can be accessed by existing cell phone technology. Today, the environmental monitoring community can select from digital applications (“apps”) for recording, processing, and sharing sensor data. Integrating air pollution and individual physiological data collected simultaneously from networked sensors and suitable apps will empower individuals and communities with information useful in reducing exposures to air pollutants.

**Present Sensor Landscape**

At the heart of all sensor systems lie the elements that respond to nearby changes in physical or chemical characteristics and the transducers that convert the responses to electrical signals. Commercially available gas sensors are based on two main principles: (1) Chemical gas sensors depend on reactions between the target gases and the sensing material as used for ozone (O₃), nitrogen dioxide (NO₂), and carbon monoxide (CO), and sometimes for carbon dioxide (CO₂) and volatile organic compounds (VOCs); and (2) Optical gas sensors measure absorption of light by species of interest, such as O₃ and CO₂ or chemiluminescence for NO₂. Infrared absorption is widely used for CO₂. Sensors for respirable particles [below 2.5 µm aerodynamic diameter] typically rely on light scattering, a widely used method to monitor PM in near real-time, although not a direct mass measurement. Table S-1 provides additional details on detection principles, concentration ranges, accuracy, and precision, as well as strengths and weaknesses for each sensor type. Table S-1 shows that while development of gas sensors is more mature than for PM mass sensors, in general, widespread field evaluation and testing are required prior to use in routine monitoring networks for most ambient outdoor and indoor monitoring applications. [Editor’s Note: Table S-1 is part of the supplemental information that can be found in the online version of this article at www.awma.org.]

**New Technologies**

WSNs incorporate recent advances in several areas of electrical engineering. These include:

- Microfabrication techniques now make possible smaller, mass-produced sensors that are lightweight and ultimately inexpensive. In addition to micro-electro-mechanical system (MEMS) sensors with tiny (mm-scale or smaller) moving parts, sensors incorporating microfluidic, optical, and nanotube elements are also being developed.
- The costs of monitoring over large geographical areas are decreasing because signals from widely dispersed sensors can travel over existing secure WSNs.
- Energy efficient radios and sensor circuits now allow for low-maintenance operation without the need for plug-in power or direct operator access.

**Microfabricated Portable PM Monitor**

Figure 1 shows a microfabricated portable air quality PM mass monitor designed to link with a cellphone for data collection, processing, and transmission. Microfabrication techniques, such as photolithography, evaporation, and etching form the structures,
conductors, and the resistive heater. They permit the PM monitor and its aluminum housing to weigh just 27 g, with a volume of only 8 cm$^3$.

A small fan at the outlet draws PM-laden air through a microfluidic structure and a virtual impactor separates particles based on a mean cutoff diameter of 2.5 $\mu$m. Larger particles exit through the pump, while smaller particles pass through a 100-$\mu$m high channel between a resistive heater and a mass-sensing oscillator. The sensor is a microfabricated piezoelectric film bulk acoustic resonator (FBAR), a common component of cell phones connected to a complementary metal-oxide-semiconductor (CMOS) oscillator circuit. The thermal gradient between the heater and the FBAR causes particles to deposit by thermophoresis. As the mass of particles collected on the FBAR increases, the oscillator frequency falls from its nominal frequency, 600 MHz, at a rate proportional to the rate of change of the mass of collected particles. At a flow rate of 1 mL/min, the estimated limit of detection for PM in ambient air is $2 \pm 1 \mu g/m^3$ for 10-min sampling.

Measuring PM mass based on the rate of change in oscillating frequency is a well-established direct mass measurement method (e.g., in the tapered element oscillating microbalance [TEOM]) that has achieved equivalency as a continuous mass monitor for PM$_{2.5}$.$^5$ Use of transparent materials in the device allows for inclusion of optical approaches, such as particle counting to measure the size distribution and, with the simultaneous mass measurement, to obtain particle effective density ($\mu g/cm^3$).$^6$ Measuring light absorption and scattering could provide insight into chemical composition and radiative forcing by the aerosol. Another benefit of the PM monitor’s small size is that it can be packaged with sensors for temperature, relative humidity, and gases and even sensors for human physiological responses such as blood pressure and heart rate.

**Stationary and Mobile Applications**

**Stationary: Indoors and Outdoors**

Limited spatial and temporal information constrains our understanding of the spatial variability of pollutants indoors and outdoors, and obscures the relationship between them. However, most monitoring and research networks include only a few monitors in a given area, often limited to specific time periods, due to the high cost to site and operate samplers.$^7$-$^10$ Indoor sampling is usually limited to a small number of homes, with a small number of samplers in each dwelling and for short time periods, days or weeks, such as the study on the relationships of indoor, outdoor, and personal air (RIOPA), as reported by Meng et al.$^11$ Even larger indoor/outdoor/personal exposure studies, such as the Detroit Exposure and Aerosol Research Study (DEARS), involving measurements twice per year (winter and summer) over three years, was limited to 40 participants during each season in one city, and only five days in each measurement period.$^{12}$

When sensors are used at stationary monitoring sites, the cost advantages of microfabricated multi-pollutant sensors (see Figure 2) permit the use of a larger number of monitors. The low cost of sensors also allows colocating multiple devices to reduce measurement uncertainty. For example, the CO$_2$ sensor shown in Figure 3 is small (33 mm x 33 mm x 14.6 mm) and inexpensive, but the quoted uncertainty is $\pm 30$ parts per million (ppm) or $\pm 5\%$ of the measured concentration. This is too high for accurately measuring changes in the atmospheric concentration of CO$_2$ with a single sensor because...
the standard error is greater than the current 2-ppm increase of CO₂ per year, while the current average is 393 ppm.\(^{13}\)

However, Honicky\(^{14}\) showed that by colocating \(N\) identical sensors that have Gaussian response functions, the standard error decreases by \(1/N\). Adding transmitters to the stationary sensor packages makes possible two-way communication over a WSN in near real-time, allowing this information to be accessed by community members and used for short-range forecasting of air pollution and alerts. Weather Bug is one example of this approach using standard meteorological sensors. [Editor’s Note: An example of installing and powering small stationary sensors appears in the supplemental information that can be found in the online version of this article at www.awma.org.]

Mobile and Personal Applications
The integration of sensors and cell phones begins to provide a new dimension to air quality monitoring. The sensors may be internal or external to the mobile device and may be worn on the body to measure personal exposure. Coupling multifunctional monitors to cell phones also enables geo-location and data transmission via a cellular network.

Dutta’s group at the University of Michigan\(^{15}\) has shown how mobile devices can power sensors via the iPhone headset plug, as well as transmit information through the wireless network. Energy to power the sensor is provided by a 22 kHz audio tone produced by the mobile device and then efficiently amplified and rectified externally to yield approximately 14 milliwatts of DC power. The effective data rate is 30 bytes/sec. These methods provide an elegant approach to obtaining data of...
high spatial and temporal resolution that have the potential to improve exposure estimates significantly.

**Digital Computer ‘Apps’**

Apps are computer programs for cell phones that users download so they can access, collect, and use specific types of information. There are many potential users and contributors of sensor data, from individuals and businesses to organizations and governmental agencies. Apps are emerging as tools for environmental research, as illustrated by recent postings from investigators at the University of Florida.16 To encourage innovation in this area, in 2011, the U.S. Environmental Protection Agency launched the ‘Apps for the Environment Challenge.’ This effort has led to development of more than one hundred new apps that access existing environmental and health databases in user-friendly interactive formats.17 Several submissions dealt with air quality, such as the Air Quality Data Explorer for the U.S.18

**Community-Based Participatory Monitoring**

Community-based participatory monitoring refers to individuals collecting data within their communities and reporting results in near real-time. This is being made possible through the development and deployment of the sensors and WSNs described above. Data collected may be used directly through apps or uploaded to a central database for integration and analysis with other data, followed by downloading summarized results, also via apps. This empowers people to plan their daily lives to avoid significant concentrations of pollutants and allergens. Apps can help decide whether to keep windows open or closed, where to go jogging, and even where to live. Two examples showing enthusiasm for monitoring by the public, although not in real-time, are given on p. 193 of Jones19 (the first citizen science experiment: simultaneous measurement of rainfall throughout Britain) and Allen20 (response to earthquakes).

Besides guiding individuals’ behavior to avoid exposure to air pollution, sensor networks could have a significant role in developing a more robust nationwide environmental surveillance system. From the perspective of environmental health scientists the application of sensors provides new opportunities to improve the spatial and temporal resolution of environmental and physiological measurements that, when made simultaneously, would greatly enhance exposure assessment and understanding of the modes-of-action of airborne pollutants. The Center for Disease Control’s BioSense system21 is a step in this direction. [Editor’s Note: See the supplemental information that can be found in the online version of this article at www.awma.org.]

**Summary**

Ongoing miniaturization of sensor technology, the increasing availability of wireless sensor networks, and the development of user-friendly applications for mobile devices, offer opportunities for improved environmental and health monitoring. Government agencies and researchers are starting to apply these advances to address science and policy questions related to the health and environmental impacts of exposure to pollutants. Decreasing costs for environmental sensors and wireless communication equipment are enabling sensor-cellphone linkages and a growing variety of apps for handling two-way data transmission, data compilation and analysis, and sharing the resulting information with the public. Deploying simple inexpensive and multifunctional sensors for routine monitoring and field studies can provide greater data density to better understand the spatial and temporal variations of pollutants and human exposure.

Widespread use of sensor networks could significantly improve our understanding of linkages between air pollutants and adverse health effects. With the addition of sensors for human physiological responses (such as blood pressure and heart rate), the suite of available environmental sensors begins to provide new opportunities for collecting human exposure data useful for epidemiologists to better link pollutants to respiratory and cardiovascular health effects. In addition, tools suitable for community-based participatory atmospheric monitoring are now appearing, that are expected to generate strong public interest and empower people to better protect their health by being more aware of adverse pollution conditions.
References


Sensors, Sensor Systems, and Monitors
The tables below describe the design and performance of the types of sensors or sensing systems that have been incorporated into commercially available monitors. The sensor element or sensing system is what undergoes a physical or chemical change. Examples include electrochemical (EC) cells and metal-oxide-semiconductors (MOS), whose responses to the target gases are read by the circuitry and recorded by data loggers. In this context the term “sensor” applies to the sensing elements, and the term “sensing system” refers to the sensor and its associated transducer circuitry [typically on printed circuit boards (PCB) where the sensors are mounted]. All sensors are part of sensor systems, but some devices use sensing systems rather than individual sensors. Since calibration instruments for O₃, NOₓ, and CO₂ contain reaction cells whose products flow across optical paths, light detectors are the transducers. Such instruments have “sensing systems” rather than “sensors.” Sensor systems also include any components that condition the incoming air before it reaches the sensing element.

Microfabrication, Micro-Circuitry, and Micro-Electro-Mechanical Systems (MEMS)
Microfabrication, micro-circuitry, and MEMS are key processes that allow for the development of sensors. Microfabrication uses techniques derived from manufacture of integrated circuits. An excellent introduction to miniaturization and microfabrication is given by Madou.

Suitability of the Sensor Technologies for Monitoring Gases in Ambient Indoor and Outdoor Air
Table S-1 summarizes the strengths and weaknesses of approaches used in current sensors, based on reading the literature and considering the technical requirements for routine air quality monitoring. Tables S-2 and S-3 provide additional descriptions and analytical characteristics of commercially available sensors. Electrochemical and metal-oxide-semiconductor gas sensors are small enough to fit onto small PCBs and the low cost of the sensor elements will allow for placement at multiple locations. However, the available literature indicates that the responses of EC and MOS sensors are susceptible to changes in pressure, relative humidity, and temperature, and may have cross-sensitivities to other gases besides the intended analytes. The commercialized optical method for O₃ has not yet been miniaturized sufficiently for the sensor element to fit with other sensors into a case as small as shown in Figure 2 of the main text. A commercially available miniature CO₂ sensor is shown in Figure 3 of the main text. All three of the optical methods in Table S-2 need to be miniaturized for cost-effective incorporation into wireless sensor networks (WSNs). Except for CO₂, handheld gas sensor systems have insufficient sensitivity for typical ambient indoor and outdoor monitoring.

Table S-2 shows manufacturers’ performance specifications for the types of sensor technologies that might be used to monitor CO, CO₂, NOₓ, and O₃ in ambient air and indoors. The first row for each pollutant has specifications for a bench-top instrument that can be used to calibrate the more portable devices that follow. Information in Tables S-1 and S-2 applies to the performance of each type of monitor as a whole, but the accuracy and precision are mostly controlled by the type of sensing technology.

Airborne Particulate Matter: Selected sensors for direct and indirect measurements of PM mass concentration are described briefly in Table S-3. Direct mass monitors use an oscillating sensor to measure the mass as a function of the rate of change in the resonant frequency. The indirect mass sensors are based on light scattering and require assumptions about density and refractive index, and/or composition to derive estimates of PM mass. Indirect devices are also affected by temperature and relative humidity. The FDMS TEOM and Scanning Mobility Particle Sizer–Aerosol Particle Sizer (SMPS-APS) are widely used commercially available methods that provide historical reference for the measurement of mass within given size ranges either directly (TEOM) or indirectly (SMPS-APS).

The FMDS-TEOM is based on an oscillating element that changes frequency due to the change in mass collected on the element. The SMPS first separates particles in the size range from about 10 nm or...
lower to about 800 nm, based on their mobility and then counts individual particles using a condensation particle counter as the detector. The APS obtains a size distribution from about 0.5 to 20 µm aerodynamic diameter by determining the time-of-flight of individual particles in an accelerating flow field. Particle density and shape factors are required to convert the size distribution to mass concentration.

Figure S-1 is a flow diagram of the prototype PM$_{2.5}$ sensor described in more detail in the main article for which a patent is pending. A microfabricated virtual impactor separates particles into the fine (<2.5 µm) and larger sizes (>2.5 µm). The fine particles are deposited on the resonator (FBAR) by thermophoresis whereas the larger particles exit through the pump. The change in the frequency of the oscillator results in a signal that is transmitted to analysis circuitry and sent to a cell phone for wireless communication. This MEMS sensor has miniaturized the technology described in U.S. patent 7,168,292 (2007).^3

Power, Installation, and Communication
Stationary sensors need to be installed and require a source of power, albeit a small amount (a few to a few hundred milliwatts), especially relative to standard air quality monitors (i.e., 10-15 amps, 120 V). Sensors can be easily attached to ubiquitous existing structures built for different purposes e.g., utility poles, to secure passive samplers and sensors that have on-board power supplies (e.g., rechargeable batteries, supercapacitors).^4

Harvesting power from utility lines can provide stable, inexpensive, and long-term power for sensors and transmitters by using microfabricated energy harvesters^5 that couple magnetically to the AC conductors. Although widely available, power lines are located higher (~7 to 30 m) than appropriate for most human exposure measurements, however, inexpensive technology for wireless transmission to the 1 m level can be used. Sensors and energy harvesters can be mechanically attached (e.g., clamped) to the power lines (with power company approval) by one person who stands beneath the power line, using a battery-powered drone, a miniature remote-controlled helicopter.~^6

Miniature integrated circuit radio chips are now available that require only 21 milliwatts for continuous wireless transmission of data over distances up to 200 meters outdoors, and some radios have wake-up features that enable them to “sleep”, using only microwatts of power, and then wake up when they receive a command. These radio chips can allow for further reductions in the cost and size of atmospheric sensors.

Community-Based Participatory Monitoring
Weather Bug
The Weather Bug network of meteorological stations’ is an example of a real-time stationary network having monitors located at multiple stations in most U.S. cities with online public access through personal computers and smart phones. One enters a zip code on the Web page (http://weather.weatherbug.com)^7 and finds today’s weather for that zip code, as well as hourly and seven-day forecasts, and other relevant weather information. Although using standard size meteorological monitors, the
access and communication with the public mimics the design of upcoming sensor networks. Data are uploaded to a central site, manipulated, and made available for use by individuals.

**Application to Human Health and Ecosystems**
The development and deployment of wireless networks incorporating multifunctional sensors has many potential applications related to the measurement and understanding of human health and ecosystems. Apart from providing data for guiding the behavior of an individual to avoid exposure to a pollutant, as described in the main text, such monitoring could have a significant role in the development of a more robust environmental surveillance system through integration with clinical health data. An example of this is with Center for Disease Control's (CDC) syndromic surveillance system, BioSense, that aggregates health data from a variety of sources in nearly real-time. Likewise, data from such a system would provide additional information that could enhance CDC’s National Environmental Public Health Tracking Network, particularly in areas where environmental data are absent. These systems will undoubtedly be augmented in the future by the integration of electronic health records (EHR) across the country as EHR systems are promulgated to meet the goals of the Health Information Technology for Economic and Clinical Health (HITECH) Act and the Patient Protection and Affordable Care Act. From the perspective of the environmental health scientist and epidemiologist such low-cost micro-scale sensors would provide new opportunities to improve the spatial and temporal resolution of environmental, physiological, and health data that would provide unparalleled insight into environmental drivers of individual and community health. For the clinician, integration with home telemonitoring of clinical information will provide pathophysiological correlation that could impact clinical decision-making, and improve clinical care and outcomes.

<table>
<thead>
<tr>
<th>Gases</th>
<th>Strengths</th>
<th>Concern 1</th>
<th>Concern 2</th>
<th>Concern 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO, O₃, NOₓ</td>
<td>Low cost, low power, small, real-time; more sensitive than MOS (metal-oxide-semiconductor) sensors</td>
<td>Interferences: CO, VOC</td>
<td>Sensitive to changes of RH, T, P</td>
<td>Drift, frequent recalibration needed, 1 yr lifetime</td>
</tr>
<tr>
<td>CO, O₃, NOₓ</td>
<td>Small size; stability, long lifetime, inexpensive</td>
<td>Sensitive to change of RH, T, P; cross-sensitivity</td>
<td>Power consumption; fragile materials</td>
<td>Typically less sensitive than EC</td>
</tr>
<tr>
<td>CO₂</td>
<td>Compact, stable to changing RH and T</td>
<td>Sensitivity depends on path length</td>
<td>Calibration may be misinterpreted or inaccurate</td>
<td>Some single beam devices auto-calibrate as if background CO₂ is 400 ppb</td>
</tr>
<tr>
<td>O₃, NOₓ</td>
<td>Accurate, stable to change in P</td>
<td>Size (not yet miniaturized)</td>
<td>Sensitive to changes in relative humidity</td>
<td>Cost</td>
</tr>
</tbody>
</table>

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Table S-2. Sensor technology and specifications for typical commercially available monitors.

<table>
<thead>
<tr>
<th>Analyzera</th>
<th>Sensor Technology</th>
<th>Rangeb</th>
<th>Accuracy</th>
<th>Precision</th>
<th>Environmental Limits</th>
<th>Response Time</th>
<th>Price USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO (8 hr: 9 ppm; 1 hr: 35 ppm)c</td>
<td>TECO Model 48C</td>
<td>IR absorption</td>
<td>0.3-100 ppm</td>
<td>± 1 %</td>
<td>0.1 ppm</td>
<td>5 to 45 °C</td>
<td>60 s</td>
</tr>
<tr>
<td></td>
<td>Langan Data-Bear, I T15d</td>
<td>Electrochemical Cell</td>
<td>2–200 ppm</td>
<td>0.5 ppm</td>
<td>0.5 ppm</td>
<td>23 to 40 °C</td>
<td>≥ 1 s</td>
</tr>
<tr>
<td></td>
<td>TSI Q-Trak Plus, 8554</td>
<td>Electrochemical Cell</td>
<td>0.3-500 ppm</td>
<td>greater of ±3% of reading or 3 ppm</td>
<td>0.1 ppm</td>
<td>5 to 45 oC</td>
<td>&lt; 60 s</td>
</tr>
<tr>
<td></td>
<td>Aeroqual Series 5004</td>
<td>Metal Oxide Semiconductor (MOS)</td>
<td>2-100 ppm</td>
<td>&lt; ±10% 20-100 ppm</td>
<td>0.1 ppm</td>
<td>0-40 °C, 5 to 95% RH</td>
<td>&lt; 150 s</td>
</tr>
<tr>
<td>CO₂ (no standard)</td>
<td>LI-COR, Model 7000</td>
<td>Non-dispersive IR absorption (NDIR)</td>
<td>0.03-3000 ppm</td>
<td>1%</td>
<td>0.01 ppm</td>
<td>5 to 45 °C</td>
<td>Fast – 0.02 s Slow – 1 s</td>
</tr>
<tr>
<td></td>
<td>TSI Q-Trak Plus 8554</td>
<td>NDIR</td>
<td>3-5000 ppm</td>
<td>±3% of reading</td>
<td>1 ppm</td>
<td>5 to 45 °C</td>
<td>20 s</td>
</tr>
<tr>
<td></td>
<td>PP Systems EGM-4</td>
<td>NDIR</td>
<td>30-5000 ppm²</td>
<td>better than 1%</td>
<td>10 ppm</td>
<td>0 to 70 °C</td>
<td>1.6 s</td>
</tr>
<tr>
<td></td>
<td>Edurevo</td>
<td>Model S-100 NDIR</td>
<td>NA</td>
<td>±30 ppm ± 5% of reading</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>NO₂ (1 hr: 100 ppb; annual average: 53 ppb)</td>
<td>API, Model 200EM</td>
<td>Chemiluminescence</td>
<td>0.05-1 ppm¹</td>
<td>5%</td>
<td>5%</td>
<td>5 to 40 °C</td>
<td>20 s</td>
</tr>
<tr>
<td></td>
<td>2B Technologies, 400</td>
<td>Depletion of ozone by UV absorbance</td>
<td>0.006-2 ppm</td>
<td>2.0 ppbv or 3%</td>
<td>2 ppbv or 3%</td>
<td>&lt;20 s</td>
<td>10 s</td>
</tr>
<tr>
<td></td>
<td>Alphasense D-4 mini</td>
<td>Electrochemical Cell</td>
<td>0.2-20 ppm</td>
<td>±100 ppb</td>
<td>8%</td>
<td>-20 to 50 °C, 15-90% RH</td>
<td>&lt;35 s</td>
</tr>
<tr>
<td></td>
<td>KWI Engg NO₂-MNS</td>
<td>Electrochemical Cell</td>
<td>0.6-10 ppm</td>
<td>2%</td>
<td>2%</td>
<td>-20 to 40 °C</td>
<td>&lt; 60 s</td>
</tr>
<tr>
<td></td>
<td>Aeroqual Series 5005</td>
<td>MOS</td>
<td>0.01-200 ppb</td>
<td>&lt; ±0.01 ppm 0-0.1 ppm</td>
<td>1 ppb</td>
<td>0 to 40 °C, 30 to 70% RH</td>
<td>&lt;180 s</td>
</tr>
<tr>
<td>O₃ (8 hr: 75 ppb)</td>
<td>API, Model 400</td>
<td>UV absorption</td>
<td>&lt; 0.6 to 200 ppb</td>
<td>better than 1%</td>
<td>1 ppb</td>
<td>10 to 90% RH, 5-40 °C</td>
<td>&lt; 20 s</td>
</tr>
<tr>
<td></td>
<td>2B Technologies, 202</td>
<td>UV absorption</td>
<td>0.005 to 100 ppm</td>
<td>1.5 ppbv or 2%</td>
<td>0.1 ppbv</td>
<td>5-10 °C</td>
<td>10 s</td>
</tr>
<tr>
<td></td>
<td>Aeroqual Series 500L5</td>
<td>MOS</td>
<td>8-500 ppb</td>
<td>8 ppbv</td>
<td>1 ppbv</td>
<td>&lt; 50 °C, 5 to 95% RH</td>
<td>&lt; 60 s</td>
</tr>
<tr>
<td></td>
<td>OMC-1108</td>
<td>Electrochemical Cell</td>
<td>0.01 to 10 ppm</td>
<td>±10%</td>
<td>10 ppbv</td>
<td>0 to 40 °C, 0 to 80% RH</td>
<td>&lt; 70 s</td>
</tr>
</tbody>
</table>

Notes: aThe first row in each section: characteristics of and performance of instruments typically used for calibration; from manufacturers’ datasheets bThe lower limit is estimated as LOD or 3 times the precision. cCurrent air quality standards in the US as a reference to ambient. ¹User selectable from 1 to 10,000 ppm. ²User selectable from 1000 to 20,000 ppm; ³User selectable from 1 to 200 ppm. ⁴OEM = original equipment manufacturer. ⁵The Aeroqual S500 has swappable heads for different gases.
Table S-3. Instrumentation for continuous measurement of PM$_{2.5}$ mass concentration.$^a$

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measurement Principle</th>
<th>Manufacturer</th>
<th>Accuracy</th>
<th>Precision</th>
<th>Limit of Detection</th>
<th>More Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct determination of mass concentration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDMS-TEOM</td>
<td>Oscillating microbalance</td>
<td>Thermo Electron</td>
<td>±0.75%$^b$</td>
<td>&lt; 10%$^b$</td>
<td>0.06 µg m$^{-3}$ (1-hr average)</td>
<td>Filter Dynamics Measurement System</td>
</tr>
<tr>
<td>QCM</td>
<td>Impaction on piezoelectric sensors</td>
<td>California Measurements</td>
<td>±0.75%$^c$</td>
<td>&lt; 10%$^c$</td>
<td></td>
<td>Quartz crystal microbalance; mass size distribution</td>
</tr>
<tr>
<td>MEMS-PM</td>
<td>MEMS Virtual impactor &amp; FBAR</td>
<td>U.C. Berkeley</td>
<td></td>
<td></td>
<td></td>
<td>Film bulk acoustic resonator</td>
</tr>
<tr>
<td>Indirect measurement of mass concentration using size distributions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMPS-APS</td>
<td>SMPS: electrical mobility; APS aerodynamic diameter; mass size distribution</td>
<td>TSI Inc</td>
<td></td>
<td></td>
<td></td>
<td>Number size distribution converted by density and shape factor to mass size distribution using both the Scanning Mobility Particle Sizer (10-800 nm) and Aerodynamic Particle Sizer (0.5 - 10 µm)</td>
</tr>
<tr>
<td>DustTrak</td>
<td>Light scattering; calibration using AZ road dust</td>
<td>TSI Inc</td>
<td>±0.1 % or ±0.001 µg m$^{-3}$</td>
<td>±0.1 % or ±0.001 µg m$^{-3}$</td>
<td>1 µg m$^{-3}$</td>
<td>Factory calibrated to Arizona Road Dust; users must calibrate for specific aerosols</td>
</tr>
<tr>
<td>Dylos</td>
<td>Light scattering</td>
<td>Dylos Corp.</td>
<td></td>
<td></td>
<td></td>
<td>Inexpensive &lt; $350</td>
</tr>
</tbody>
</table>

Notes: $^a$The current air quality standard in the US for 24 hr average is 35 µg m$^{-3}$; $^b$From Chow et al.; $^c$Manufacturer’s specifications; $^d$Experimental models; “See Sioutas et al”; $^e$Not Available.

References
7. For example, for weather in Berkeley, CA: http://weather.weatherbug.com/CA/Berkeley-weather.html?zcode=z6286.