Air Sensor Study Design

Details Matter

Careful study design is vital for ensuring that data collected using sensors are of sufficient quality to meet study objectives. Here, we describe three important steps to follow when designing a sensor study.

The availability of and interest in small, inexpensive, easy-to-use, portable air sensors continue to grow rapidly. The lower cost and portability of these sensors compared with traditional air quality monitors mean that they can be deployed with greater ease and can be used by individuals in novel ways, such as on vehicles or in dense networks. Many users are excited by the new technology and opportunities to measure air quality, and are eager to get out in their communities and start collecting data. However, in the midst of this excitement, vital study design steps (summarized in Figure 1) are often rushed or overlooked, leading to disappointment and missed opportunities. Beyond setting objectives and planning study logistics, there are three important sensor-specific study design considerations: (1) selecting a sensor system(s), (2) siting the sensor(s), and (3) performing field and data activities.

Figure 1. Sensor study design process.

Selecting a Sensor System

Sensor technology is evolving rapidly. There are dozens of air sensors on the market that cost between US$5 and US$500, and many more are currently in development. While the availability of an array of different sensors is exciting, it is often difficult to understand how a sensor will perform based on manufacturers' specifications and laboratory evaluations. Recent efforts by the U.S. Environmental Protection Agency (EPA) (https://www.epa.gov/air-research/air-sensor-toolbox-citizen-scientists) and the South Coast Air Quality Management District (SCAQMD) (http://www.aqmd.gov/aq-spec) provide insight into sensor performance. Currently, there are many particulate matter sensors and several ozone, nitric oxide, nitrogen dioxide, and carbon monoxide gas sensors that are capable of detecting ambient concentrations; however, sulfur dioxide and volatile organic compound sensors are not yet sensitive enough to measure ambient conditions and suffer from many interferences.

Whenever possible, sensor selection should be based on the objectives of the study. Important considerations include the target pollutant, the expected range in concentrations, and the sensor's ease of use, sampling frequency, interferences, and maintenance requirements. EPA's *Air Sensor Guidebook*[1] is a useful resource; it provides summaries of common pollutants, examples of sources, and concentration ranges that one might expect in ambient air.

Equally important considerations are the hardware and software components of the sensor system, which incorporates data storage, processing, transfer, and visualization capabilities. These sensor system components are critical and often overlooked when selecting a sensor. For example, some sensor systems come equipped with Bluetooth and data management

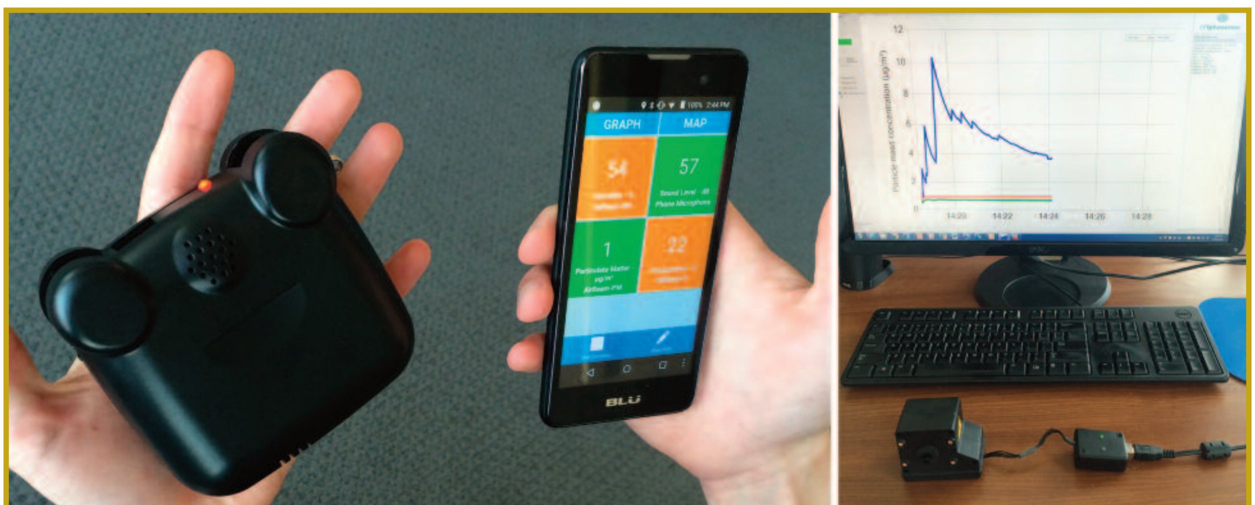

Figure 2. The AirBeam system (left) includes a particulate matter sensor, Bluetooth data communications, and the AirCasting app and website for data visualization. The Alphasense OPC (right) is a particulate matter sensor with a hardware-to-computer interface. These are two selected air sensor systems among many available.

TIPS: For Selecting a Sensor System

- Identify potential inferences and ensure those parameters are measured.
- Consider all of the factors involved in getting the data from the sensor to a computer for analysis and interpretation.
- If using a cloud data service and data ownership is important, determine who will own the data (the user or the sensor company).

and visualization capabilities, while others require the user to integrate other technologies into the system to achieve these functions (see the example in Figure 2). Data management can be particularly challenging due to the high temporal resolution (i.e., 1 second to 1 minute) of data collected by sensors, which results in the collection of large volumes of data that can be on the order of 60 to 3,600 times larger than the hourly data sets reported by traditional monitors.

Many of the current air sensors on the market are subject to sizable interferences from other pollutants, or from meteorological conditions such as relative humidity or temperature.[2] Sensor developers typically disclose whether there are any interferences that may influence a sensor measurement; however, it can be difficult to anticipate how significantly a sensor may respond to an interferent. It is important to identify the potential interferences exhibited by a sensor of interest and determine if the effects can be minimized. It may be possible to collect additional measurements of interfering pollutants or meteorological variables so that the relationship between the target pollutant and the interfering pollutant can be determined and the data can be corrected during post-processing. When using additional measurements to post-process data, it is important to keep in mind that those measurements have their own uncertainties that must also be characterized.

Siting the Sensors

The relatively small size and portability of low-cost sensors makes them suitable for deployment in almost any environment, offering unique opportunities to monitor air quality in novel locations and under conditions where traditional

Figure 3. Examples of air sensor deployments.

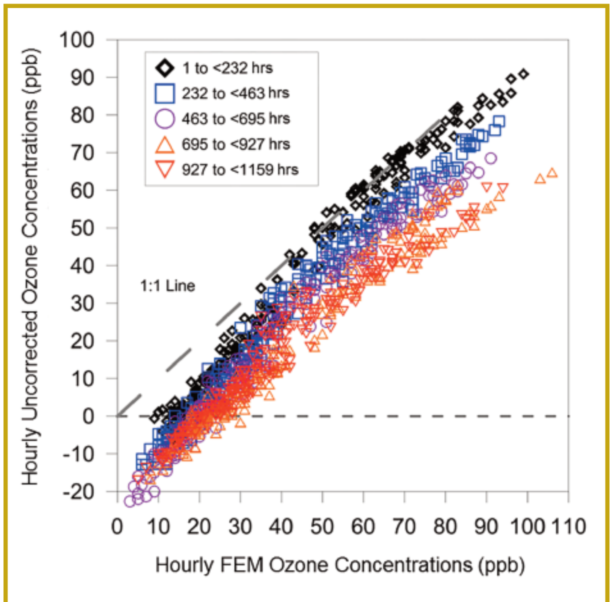

Figure 4. Hourly ozone from a sensor exhibiting drift over time versus a reference monitor.[3] Colors and symbols show hours since the start of the study in increments of approximately 10 days.

monitoring equipment–limited by physical space, power, security, and other infrastructure requirements–cannot be easily installed. Air sensor devices have been deployed in a variety of ways, including at a traditional monitoring site, secured on a tripod in a field or on the side of a building, or carried by a person walking, on a bike, or in a vehicle (see Figure 3).

Siting considerations for low-cost sensor devices include many of those that are important for siting traditional, regulatory monitors—the measurement scale of interest, environmental exposure, and security. In addition to these considerations, low-cost sensor users are faced with challenges related to interferences and sensor mobility, such as the need to ensure proper airflow to the sensor inlet during measurement collection. Channeling of air around a sensor shelter or around nearby structures can radically impact concentration readings. Furthermore, unlike traditional air quality instruments that have pumps to draw large volumes of air into them, sensors often have weak fans or no forced airflow at all. Blocked or restricted airflow can result in measurement artifacts and/or biased data. Personal safety (particularly during mobile deployments) may also be an important consideration, especially for devices with visually engaging real-time data displays.

Performing Field and Data Activities

Once the sensor and siting location appropriate for the study objectives have been selected, data collection steps need to be carefully planned. Unlike traditional monitors that are routinely adjusted by calibration activities, many of the low-cost sensors currently on the market cannot be calibrated by the user. As an alternative, users can assess sensor accuracy by comparing measurements to data from a local air quality agency or AirNow.gov (https://airnow.gov/), collocate a sensor with a regulatory-grade instrument to ensure measurements co-vary and are the right order of magnitude, or collocate multiple sensors to examine precision.

Once data collection has begun, it is important to periodically review the collected data to identify and correct any problems that arise and routinely inspect and service the sensors according to the manufacturer's specifications. Data assessment early in the study is necessary to make any needed adjustments to the study design to better meet the objectives. Common findings that may require study design changes and related considerations include

- **Substantial interferences**—consider measuring temperature and humidity at a minimum, in addition to interfering pollutants.
- **Drift**—consider collocation with another instrument.
- **Fouling**—periodically collocate the sensor with a sensor that has not been exposed to the same environment to assess whether fouling may have occurred over time. For example, some gas sensors have a tendency to degrade over time and PM sensors may accumulate dust on their optical systems.

Post-study activities include data validation, analysis, and interpretation. As described above, data validation is typically made easier by periodic data review and study design evaluation. Even so, data analysis challenges may include accounting for interferences and sensor drift; Figure 4 shows an example

TIPS: For Siting Sensors

- For mobile deployments, consider the frequency of the sensor measurement relative to the speed of the mobile platform.
- Ensure that the sensor inlet is exposed to consistent airflow over the course of the study, regardless of wind direction.

TIPS: For Collecting Data

- If a sensor cannot be user-calibrated, deploy several sensors side-by-side for several days, operate them over a range of pollutant concentrations and weather conditions, and compare the measurements among sensors to examine data consistency.
- Trends in sensor measurements are generally more reliable than the absolute values, as long as drift and known temporal variability (e.g., temperature sensitivity) are accounted for during data analysis.
- Follow ongoing sensor evaluation and sensor messaging efforts by EPA (http://www.epa.gov/air-research/air-sensor-toolbox-citizen-scientists) and SCAQMD (http://www.aqmd.gov/aq-spec).

of drift exhibited by an ozone sensor. Drift can be corrected by applying a time-dependent correction factor, provided a reference is available to verify the true value. The large volume of data and greater variability associated with high time-resolution measurements can make it more challenging to identify outliers or events.

Finally, sensor data interpretation can prove challenging, especially when comparing short-term measurements to air quality standards or other health benchmarks. Most health standards, such as the Air Quality Index, are based on exposure times of 1-hr, 8-hr, or 24-hr duration. Health messaging for 1-second or 1-minute concentrations collected by non-regulatory sensors is currently focused on planning personal activity choices, such as messaging developed by EPA as part of the Village Green (https://www.epa.gov/air-research/village-green-project) project.

Summary

Small, low-cost sensors provide opportunities for exploring air quality in ways never before possible by such a broad audience. As in any air pollution study, it is imperative to focus on the details of the study design so that results are meaningful and meet the project goals. **em**

Tim Dye is a senior vice president, **Ashley Graham** is an air quality scientist and project manager, and **Hilary Hafner** is a senior vice president and the manager of the Environmental Analysis Division at Sonoma Technology Inc. in Petaluma, CA. E-mail: **tim@sonomatech.com**.

References

1. Williams, R.; Kilaru, V.; Snyder, E.; Kaufman, A.; Dye, T.; Rutter, A.; Russell, A.; Hafner, H. *Air Sensor Guidebook;* EPA 600/R-14/159; U.S. Environmental Protection Agency, 2014; available online at http://epa.gov/research/docs/air-sensor-guidebook.pdf.
2. Lewis, A.C.; Lee, J.D.; Edwards, P.M.; Shaw, M.D.; Evans, M.J.; Moller, S.J.; Smith, K.R.; Buckley, J.W.; Ellis, M.; Gillot, S.R.; White, A. Evaluating the performance of low-cost chemical sensors for air pollution research; *Faraday Discussions* **2016**, *189*, 85-103.
3. MacDonald, C.P.; Roberts, P.T.; McCarthy, M.C.; Rutter, A.P.; Dye, T.S.; Vaughn, D.L.; Minor, H.A.; Smith, K.M.; Henshaw, G.; Nester, S.; Morrow, D.; Winegar, E.; Sweet, J. Measuring spatial variability in ozone concentrations using a small-sensor network. Presented at the *A&WMA Air Quality Measurement Methods and Technology Conference, Sacramento, California, November 19–20, 2013, by Sonoma Technology, Inc.; Aeroqual Ltd.; Providence Engineering and Environmental Group, LLC; and the San Joaquin Valley Unified Air Pollution Control District.*