AQ-SPEC
Air Quality Sensor Performance Evaluation Center

Field Evaluation of Low-Cost Air Quality Sensors

Field Setup and Testing Protocol

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1. Background

1.1. "Low-cost" air quality sensors

Manufacturers have recently begun marketing low-cost air quality sensors to measure air pollution, and considering how fast the air monitoring sensor technology is evolving, it is likely that the availability of such sensors in terms of both type and numbers will continue to grow in the near future. These devices, provided they produce reliable data, can significantly augment and improve current ambient air monitoring capabilities that now predominantly rely on more sophisticated and expensive fixed-site federal-reference monitoring devices and methods. In particular, these devices can be deployed near specific sources to better characterize local levels of air contaminants or over a wider geographic area to identify spatial and temporal trends. Given their "low-cost", these sensors are becoming an attractive means for local environmental groups and individuals to independently evaluate air quality. The new approach is receiving acknowledgement from the U.S. EPA and will likely introduce a paradigm shift to supplement traditional air monitoring by air regulatory agencies with community-based monitoring using air monitoring sensors. Due to their "low-cost" and ease of use, such devices also have the potential of becoming highly effective tools for introducing and engaging students and community groups in air quality matters.

There are, however, no independent objective means by which these devices can be evaluated, and data from these monitors are usually accepted at face value with no opportunity to evaluate their accuracy and overall quality. In fact, preliminary tests performed in the U.S.[1-3] and in Europe[4-7] suggest that many of the commercially available air monitoring sensors have poor to modest reliability, do not perform well in the field under ambient conditions, and do not typically correlate well with data obtained using "standard" measurement methods employed by regulatory agencies. Poor quality data obtained from unreliable sensors, especially that in conflict with data obtained from traditional and more sophisticated monitoring networks, may not only lead to confusion but may also jeopardize the successful evolution of this "low-cost" sensor technology. Therefore, there is an urgent need to better characterize the actual performance of air monitoring sensors as well as to educate the public and users about the potential and limitations of these devices.

1.2. Air Quality Sensor Performance Evaluation Center (AQ-SPEC)

In an effort to provide the public with much-needed information about the actual performance of commercially available "low-cost" sensors, the South Coast Air Quality Management District (SCAQMD) has established the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) to perform thorough performance characterization of currently available sensors using both field- and laboratory-based testing. In the field, air quality sensors are operated side-by-side with U.S. EPA approved Federal Reference Methods and Federal Equivalent Methods (FRM and FEM, respectively) that are routinely used to measure air pollutants concentrations for regulatory purposes (see Appendix). All sensors are evaluated in triplicates and for a period of two months to provide better statistical information of overall performance. In the lab, a state-of-the-art characterization chamber is used to challenge the sensors with known concentrations of different particle and gaseous pollutants under controlled environmental conditions.

This document describes the field testing procedures used by SCAQMD Staff to evaluate the performance of commercially available "low-cost" air quality sensors under ambient conditions in the South Coast Air Basin. All data collected, documentation developed, and testing results obtained during this project are organized and posted online as part of the AQ-SPEC website (www.aqmd.gov/aq-spec) and made available for free to educate the public on the capabilities of commercially available air quality sensors and their potential applications. Sensor-related events and workshop information are also posted on this website.

1.3. Sensor selection criteria for AQ-SPEC's field evaluation

Sensors are selected for testing at AQ-SPEC (both field and laboratory) based upon the following criteria:

- The sensor shall be commercially available.
- The sensor shall measure one or more of the U.S. EPA National Ambient Air Quality Standards (NAAQS) criteria pollutants, air toxics, pollutants of concern and non-air toxics. Examples of the targeted gases and particles are carbon monoxide (CO), ozone (O_3), nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), hydrogen sulfide (H_2S), and methane (CH_4).
- The sensor shall have high sensitivity at ambient level and low concentrations.
- The sensor shall provide real- or near-real time measurements. In order to be considered for evaluation, a sensor must have the ability to either store data internally or log data to a computer via a supplied software or have a serial port output. Logging data to a cloud based server is also acceptable.
- The sensor shall have the capability of continuously running for at least two months, using AC or DC power.
- The market cost of the sensor shall be less than $2000. If a device presents as a multi-pollutant sensor box, then the cost per pollutant type (individual sensor) should be less than $2000.

2. Methods

2.1. Field Deployment

AQ-SPEC staff actively searches for commercialized air quality sensors that fit the evaluation selection criteria. Funding is allocated for purchasing or leasing sensors in triplicate. As soon as the sensors are received, they are placed in queue for field evaluation. Usually, sensors can be deployed within one month after they have been received.

AQ-SPEC evaluates low-cost air quality sensors under ambient conditions through a field deployment at a SCAQMD air monitoring station (AMS). Sensors are typically tested as off-the-shelf products without prior modification, or calibration (zero, span, and accuracy). Sensors are operated according to the sensor manufacturer's user guide or manual. If specified by the sensor manufacturer's user guide or manual, the sensors may undergo routine maintenance throughout the study. Routine maintenance may include but is not limited to filter replacement, zero calibration, flow rate checks, date/time synchronization, and battery change.

The air monitoring stations are equipped with FRM), FEM, or BAT monitoring instruments which are routinely used to measure the ambient concentrations of gaseous or particulate pollutants for regulatory purposes. The low cost sensors are deployed side by side with the FRM, FEM, or BAT monitoring instruments and the data comparability between the two methods is the primary tool used in the evaluation process. To ensure statistically relevant data sets, sensors are deployed in triplicate and for a period of two months. Deployments in triplicate allows for intra-model comparability statistics between the three sensors and the ability to detect potential sensor failure or malfunctions. Sensors that are ruggedized and designed for ambient air monitoring purposes are typically mounted outside on the protective railing of the AMS. Sensors that are not ruggedized for inclement weather and designed for ambient air monitoring conditions are deployed in a custom-built sensor shelter.

2.2. Sensor Shelter

A louvered aluminum shelter was designed and constructed to house the non-ruggedized air quality sensors from inclement weather conditions, such as heavy rain, strong winds and harsh sunlight. The shelter's main cabin is approximately 3 x 3 x 3 (L x W x H in feet) with louvered vents and a mesh floor to allow for air circulation. The shelter has three aluminum mesh shelves upon which the sensors are placed for the extended field deployment. The shelter is designed in a manner to provide movement of air through the enclosure in order to provide a near-ambient conditions environment for both gases and particulate matter.

Figures 1a-c. AQ-SPEC's Sensor Shelter at Rubidoux AMS

2.3. Site Locations

2.3.1. SCAQMD Riverside-Rubidoux Air Monitoring Station

The SCAQMD Riverside-Rubidoux (RIVR) Air Monitoring Station (AMS) is a fully instrumented air quality station that is part of the EPA National Core Network (NCORE). NCORE is a multi-pollutant network that integrates advance measurement systems for particles, pollutant gases, and meteorology. The station features FRM instrumentation for the NAAQS gas pollutants and FRM and FEM instrumentation for NAAQS particulate matter. The air quality station is also equipped with BAT) for particle number, black carbon, and other air toxics. Elevation at the site is 248 meters with GPS coordinates: Latitude: 33° 59' 58"N Longitude: 117° 24' 57"W. For a complete report on the RIVR site, view the Quality Assurance Site Survey Report for Riverside-Rubidoux.

2.3.2. SCAQMD Long Beach Route 710 Near-Road Air Monitoring Station

The SCAQMD Long Beach Route 710 Near-Road AMS (710NR) is an air monitoring station that is part of the EPA national near-road monitoring network designed to provide real-time near roadway measurements of NO_2. The station features FRM for NO_2 and $PM_{2.5}$ along with FEM for $PM_{2.5}$. The air quality station is also equipped with best available technology (BAT) for particle number, black carbon, and other air toxics. The location of the site is 20 meters from the roadway with an elevation of 12 meters and GPS coordinates: Latitude: 33° 51' 34"N Longitude: 118° 12' 01"W. For a complete report on the 710NR site, view the Quality Assurance Site Survey Report for Long Beach Route 710 Near Road.

2.3.3. Site Specific Factors

The field evaluation reports generated by AQ-SPEC contain data collected at our testing station during a specific 30- to 60-day period with specific conditions that may not be duplicated or simulated. Factors that may affect sensor testing include site location, season, time period, and weather conditions including temperature, relative humidity, pressure, and wind speed/direction. The overall sensor performance of a sensor is likely to be affected by any environmental conditions that are significantly different from those experienced at our site during the time period of testing.

2.4. Reference Instrumentation

2.4.1. Particle Monitors

The reference (FEM or non-FEM) continuous and semi-continuous particle monitors used to conduct particle size distributions and mass concentration measurements are listed below:

- Dust Monitor by GRIMM (model EDM180, Ainring, Germany): The EDM 180 spectrometer provides high-resolution real-time aerodynamic measurements of PM_{10}, $PM_{2.5}$, $PM_{1.0}$, TSP and coarse PM particles. The EDM 180 measures light-scattering and is designated as class III equivalent method EQPM-0311-195 by the U.S. EPA for $PM_{2.5}$.
- Met One 1020 Beta Attenuation Monitor (BAM) for $PM_{2.5}$: The Met One BAM measures and records hourly particulate mass concentrations in ambient air. The BAM 1020 uses beta ray attenuation to calculate collected particle mass concentrations.
- Met One 1020 Beta Attenuation Monitor (BAM) for PM_{10}: The Met One BAM measures and records hourly particulate mass concentrations in ambient air. The BAM 1020 uses beta ray attenuation to calculate collected particle mass concentrations.

2.4.2. Gas Monitors

The reference (FRM or BAT) continuous gas monitors used to conduct gas concentrations measurements for the field evaluation include:

- APMA 370 CO Analyzer by Horiba: The APMA 370 is a non-dispersive cross modulation infrared analysis monitor that measures CO. The APMA 370 is designated as a reference method RFCA-0506-158 by the U.S. EPA (40 CFR Part 53).
- 42i NO-NO_2-NO_x Analyzer by Thermo Scientific: The 42i uses gas phase chemiluminescence detection to perform continuous analysis of NO, total NO_X and NO_2. The 42i is designated as a reference method RFNA-1289-074 by the U.S. EPA (40 CFR Part 53).
- 49i O_3 Analyzer by Thermo Scientific: The 49i is based on the principle that ozone molecules absorb UV light at a wavelength of 254 nm. The 49i is designated as an equivalent method EQOA-0880-047 by the U.S. EPA (40 CFR Part 53).
- 43i-TLE SO_2 Analyzer by Thermo Scientific: The 43i-TLE is trace level-enhanced pulsed fluorescence analyzer operates on the principle that SO_2 molecules absorb ultraviolet (UV) light and become

excited at one wavelength, then decay to a lower energy state emitting UV light at a different wavelength.

- Serinus 55 H_2S Analyzer by American Ecotech: The Serinus 55 uses UV fluorescent radiation technology combined with an external thermal converter to detect H_2S.
- Methane/Non-Methane/Total Hydrocarbon Analyzer (Model 200T-S) by VIG Industries: The 200T-S measures concentrations of hydrocarbons in gas mixtures in the air and can separate the methane component from the non-methane component by using a GC column.

3. Sensor Evaluation

3.1 Field evaluation parameters

The field evaluation of the sensors is based on a side-by-side comparison between the three sensor devices and the FRM/FEM instrument(s) measuring the same pollutant(s). A series of performance-related parameters which would affect air quality measurements in the field are evaluated. These parameters include:

- Intra-model variability
- Data recovery
- Linear correlation coefficient (R^2)

3.1.1. Intra-model variability

Intra-model variability is related to how close the measurements from three units of the same sensor type are to each other. It is evaluated through a set of descriptive statistical parameters, such as mean, median, and standard deviation.

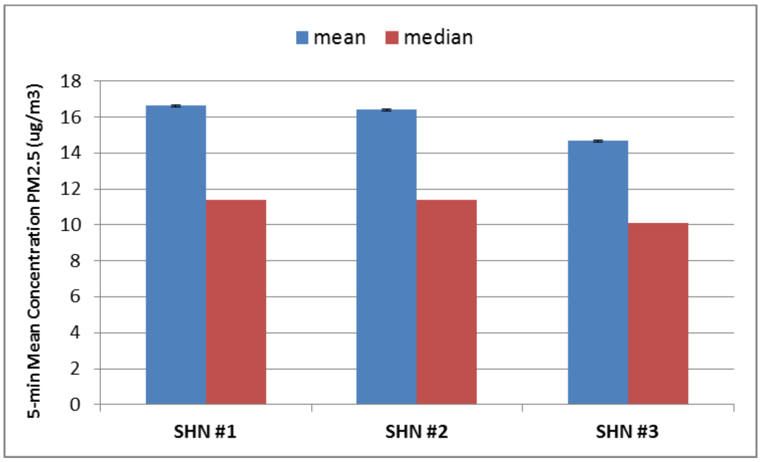

Figure 2. An example of the intra-model variability for three PM sensors

3.1.2. Linear correlation coefficient (R^2)

This parameter expresses the strength of the linear relationship between the average measurements from the three sensor tested and the corresponding reference instrument values. The paired data set is entered in an excel spreadsheet and a best-fitting (linear) regression curve is calculated along with the corresponding correlation coefficient (R^2), slope, and intercept values. An R^2 approaching the value of 1 reflects a near perfect agreement between the sensors and FRM/FEM readings, whereas a value of 0 indicates a complete lack of correlation.

3.1.3. Data Recovery

Data recovery is calculated using a percentage ratio of the number of valid sensor data points over the total number of data points collected during the testing period (e.g. 10 hours of testing at 1-min time resolution results in up to 600 data points in total). Completeness is an important factor for producing reliable and representative data, as is indicated in the EPA guidelines for regulatory data collection.

$$\text{Data recovery (\%)} = \frac{N_{\text{valid data}}}{N_{\text{test period}}} * 100$$

where,
$N_{\text{valid data}}$ is the number of valid sensor data points during the testing period
$N_{\text{test period}}$ is the total number of data points for the testing period (from start to end)

3.2 Field Testing Procedures

Before the start of an evaluation, a bench test at SCAQMD is performed. The bench test involves:

- Reviewing sensor documentation including the manual or operating procedures
- Evaluating power options: cable, battery, solar
- Evaluating data acquisition options: local storage, laptop data logging, cloud based
- Evaluating data output format to ensure a usable format
- Evaluate functionality of On/off switch to test whether sensors powers up properly

Upon successfully passing of the bench test, the sensors are brought to one the SCAQMD air monitoring stations. If the sensor is ruggedized for inclement weather, the sensor may be mounted on to a railing on the top of the air monitoring station. If the sensor is not ruggedized or not mountable, the three units of the same sensor model are placed on a shelf in the sensor shelter enclosure. Adequate power is provided for the sensors and data acquisition is established according to manufacture specification or sensor capabilities. Sensors are then exposed to ambient air for a period of 30-60 days. Sensors are checked once a week to ensure that they are operating properly and continuously data logging. If data is stored locally, collection of the data takes place at a reasonable frequency to ensure that data is not overwritten.

Figures 3a-c. AQ-SPEC's Sensor Field Evaluation Mounting Examples

3.3 Data Analysis

Reference instruments and sensor data are first validated following basic QA/QC procedures (i.e., obvious outliers, negative values and invalid data points are eliminated from the data-set). Valid data is averaged over 5-min, 1-hour, and 24-hour intervals, and data from the sensors and the reference instrument(s) is matched by date/time. Statistical analysis is then conducted to quantitatively evaluate the parameters as described in sections 3.1.1. – 3.1.3.

4. Study Limitations

It must be recognized that the field evaluation of air quality sensors is limited in some aspects. First, similar to many other field evaluations, the ambient environment is specific to its location and time of the year. The tested ambient environment could neither be controlled nor duplicated. Therefore, the performance of the sensor under significantly different environmental conditions may not be duplicated. To resolve this limitation, sensors, which have shown acceptable performance, are brought back to SCAQMD's laboratory for testing in a characterization chamber.[8] Second, the majority of the sensors evaluated in the field are not ruggedized, and might be sensitive to harsh sunlight, heavy rain and inclement weather conditions. Therefore, those sensors are field-tested inside an aluminum enclosure. While the enclosure minimizes the effect of extreme weather conditions, the louvers may slightly affect the concentrations of PM or gases in the enclosure.

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Appendix

Reference methods

Federal Reference Method (FRM): A FRM is an "EPA approved" method, sampler or analyzer that utilizes the measurement principles and calibration procedures specified in the Code of Federal Regulations (40 CFR Part 50).

Federal Equivalent Method (FEM): A FEM is an ambient air monitoring method that has been designated by EPA as an equivalent method under 40 CFR Part 53.

To be considered as a viable FRM/FEM candidate, a potential measurement technique must:

- Provide accurate and reliable measurements
- Be relatively free of significant interference from gases or other agents that may occur in ambient air
- Provide continuous or nearly continuous measurements in near real-time
- Be commercially available at modest or reasonable cost
- Be reasonably easy and convenient to operate by typical air monitoring personnel to produce measurements of good accuracy and precision
- Be reasonably and routinely field-deployable for use as a quality assurance reference in monitoring networks

Table A1. List of sensors currently available for evaluation within AQ-SPEC (updated on 01/03/2017)

Sensor	Compound(s) Measured
2B POM	O_3
3M AQM	PM, NO_2, NO, VOC
AeroQual Ozone S-500	O_3
AethLabs (microAeth)	Black Carbon
Air Quality Egg Version 2 O_3/SO_2	O_3 and SO_2
Air Quality Egg Version 2 CO/NO_2	CO and NO_2
Air Quality Egg Version 1	PM, CO, NO_2
AirBeam PM monitor	$PM_{2.5}$
Alphasense B4	O_3, CO, CO_2, H_2S, SO_2, NO, NO_2, VOC
Alphasense B4 NO_2 (Alphasense ISB)	NO_2
Alphasense B4 NO_2 with E-chem 328 board	NO_2
Alphasense B4 Ozone (Alphasense ISB)	O_3
Alphasense B4 Ozone with E-chem 328 board	O_3
Alphasense OPC N2	PM fractions
AQ Mesh (V3.0)	NO, NO_2 and O_3, CO, and SO_2
AQ Mesh (V4.0)	NO, NO_2 and O_3, CO, and SO_2
AQMD E-Box (Dylos, Yoctopuce Met, Valarm)	Particle Count, T, RH, BP

AQMD Pilot Study	PM
Awair	T, RH, CO_2, VOC, dust
Cube	T, RH, CO_2, VOC
Dylos DC1100/DC1700	Particle Count
ELM (1st deployment)	Multi-gas (non-VOC) and PM
ELM (2nd deployment)	Multi-gas (VOC) and PM
Foobot	$PM_{2.5}$
Hanvon N1	$PM_{2.5}$
Landtec AQ Mesh (V1)	NO, NO_2 and O_3, CO, and SO_2
Libelium	Multi-gas (VOC) and PM
MetOne Community Monitor	PM
MetOne E-Sampler	PM
Origins Laser Egg	$PM_{2.5}$
Partector	LDSA (PM)
Purple Air PA-I	PM_{10}, $PM_{2.5}$, PM_1
RTI MicroPEM	$PM_{2.5}$ (real-time & integrated)
SDL307 mini laser	PM_{10}, $PM_{2.5}$
Sensaris Eco PM	$PM_{2.5}$ and VOC, T, RH
Shinyei PM Sensor	$PM_{2.5}$
Smart Citizen	NO, NO_2, CO, RH, T
Spec Sensors w/ Intel Edison	O_3, NO_2, SO_2, CO
Speck (CMU) Airviz, Inc, Version 1	$PM_{2.5}$
TSI AirAssure	$PM_{2.5}$
Unitec Sense-it	CO, NO_2, O_3
Yoctopuce VOC	VOC
Yoctopuse VOC w/Valarm	VOC

Reference instrument:
An analyzer is calibrated (or re-calibrated):
- upon initial installation;
- following physical relocation;
- after any repairs or service that might affect its calibration;
- following an interruption in operation of more than a few days;
- upon any indication of analyzer malfunction or change in calibration;
- at some routine interval (see below).
  a) FRM gas analyzers are calibrated using certified gas cylinders every 6 months, and span calibrated before the start of testing a new sensor
  b) FEM GRIMM dust monitor is regularly maintained as indicated by the instrument manufacturer. Maintenance includes filter change, tubing flushing with clean air, memory card restoration. GRIMM dust monitor is sent back to the manufacturer for re-calibration every 12 months