Low Cost Sensor Calibration Options

Lower cost sensors ($100-500) represent a unique class of air monitoring devices which may provide for more ubiquitous pollutant monitoring. They vary widely in design and measure pollutants ranging from ozone, particulate matter, to volatile organic compounds, among others. Many of these sensors provide for continuous air quality measurements and wireless data transmission. However, data quality from such devices is a concern. Three straw-man approaches to improve upon the usability of such measurements were considered as part of the 2013 Air Sensors Workshop. Findings from the breakout devoted to this topic are summarized.

By **Ron Williams**, Tim Watkins, and Russell Long

Ron Williams, Tim Watkins, and Russell Long are all with ORD's Office of Research and Development, Research Triangle Park, NC. E-mail: williams.ronald@epa.gov

The Straw-Man Approach

The 2013 Air Sensors Workshop had a primary goal of moving past previous expert discussions on discovery of low cost sensor technologies[1,2] and how data from such sensors could be used to their full advantage. One key concern about these technologies was the uncertainty of their data in that often no direct means of sensor calibration was being provided by the sensor developer. As explained further in this article, there are a multitude of reasons for this lack of what most monitoring experts would consider to be a necessary feature of any air quality sensor (user response calibration). This leaves the user (often private citizens with no scientific training) with collecting data which may or may not be accurate or even realistic. To help frame a discussion about this concern and how it might be resolved, three straw-man calibration approaches were developed prior to the workshop. They were provided to registrants in advance for their consideration. Subsequent breakout panels consisting of more than 40 experts having backgrounds in sensor development, environmental monitoring, regulatory affairs, data signal processing, or citizen science then critically examined each straw-man approach. The value of each approach was considered and summary conclusions established based upon the likelihood of success of each approach and/or its acceptance by the lower cost sensor user community. Key features of each approach are defined in Table 1 and discussed in depth below.

Option 1. Use of a signal-based (wireless) calibration technique

State and Federal air quality monitoring platforms are often collecting (and some even reporting) near real-time gas and particulate matter concentrations of select air pollutants via local (State) or Federal (AirNow) venues. If it was possible to obtain telemetry from these monitoring locations and broadcast it to the surrounding area it would provide the means for receiving units (wireless-based sensors) to perform single point calibration of their response. Such telemetry might be broadcast using a local signal (typically within 500 meters of the transmitter) and would require potential "users" of the calibration data to travel to the site to acquire the data. The local air monitoring station operator would have to agree to share their output data in real time. It is uncertain who would provide resources to broadcast the signal to others. An alternative would be to simply have "users" acquire data from the nearest available website which would have some degree of data relay impact between the actual measurement time and its public reporting (expected to be > 5 minute time delay). How might such options be advantageous to users?

If users had the means of zeroing their device immediately followed by offsetting the response based on the output from the local air monitoring station it would yield a zero and span approach which should be inherently more valuable than doing no calibration check at all. It would however, be limited to the scale of the pollutant concentration encountered (with a potential lack of data at either the high or low detection range of the sensor resulting in less than a full understanding of the true linearity impact across the sensor's full range). A key feature of this approach would be the need for sensor developers to develop a built-in process by which a calibration signal could be received and then automatically processed. This would seem to be a fairly simple process but most of the effort to date would appear to be on the theory of such an approach with only limited examples of such attempts.

Option 2. Development of low cost (direct) sensor calibration kits for sale/distribution to sensor developers/users

It is peer- recognized that the direct calibration of a sensor would be the gold standard. Such a calibration approach might involve either one of two techniques: (1) challenging the inlet or contact surface of the sensor to a gas of known concentration, or (2) in the case of sensors having some defined response (e.g., resistance/conductance, voltage), activating a circuit that would establish some pre-defined output and would in turn establish the concentration readout of the device. We considered each of these separately with discussions focusing on gas-phase sensors (e.g., CO, NO_2, O_3). It did not seem practical to consider either of these techniques for calibration of particulate matter-based sensors.

One primary positive outcome from directly challenging the sensor surface with a gas of known concentration (technique #1) is the assurance that the challenge condition is well defined. One knows the concentration and purity of the gas being applied, that direct contact of the gas and sensor interface is occurring, and that one might be able to maintain the residence time of the gas on the interface to overcome response (delay) features. Calibration gas bottles are relatively inexpensive (high purity gas in small portable bottles typically can be obtained for ~ $100) and there is already an infrastructure (vendors) who produce and sell such bottles in a wide variety of single as well as multiple gas concentrations.

Many of the low cost sensors being widely distributed for both the lower cost as well as the mid-range sensor market, have response curves established not on the basis of a direct chemical challenge at the time of their sale but on the basis of a theoretical response of a batch or production example. Therefore, if one establishes an electronic or electro-mechanical means (technique #2) of challenging the sensor to a known effect (resistance/conductance, etc), the resulting output of the sensor (reported environmental concentration) could be rescaled to some pre-established value. Of course, one would have to know what the theoretical response is supposed to be based upon manufacturer's specifications. Both of the techniques being considered would be dependent upon the user having the skills and necessary supplies to conduct the calibration.

Option 3. Use of collocated data from more recognized (FRM/FEM or research grade) monitors to normalize response

State and Federal air quality monitoring platforms often collect a wide variety of pollutant measures. These include the criteria gases (CO, NO_2, O_3, SO_2) and particulate matter. If one did not have the ability to consider either technical approach options 1 or 2 as defined above, a third approach would offer the means of converting raw (non-calibrated) data into that of more acceptable quality. Data (either with short time resolution or that with longer integration periods) from State and Federal air quality systems could be obtained and then used to normalize archived lower cost sensor output. Such an approach would not require lower cost sensor developers to reconfigure hardware/software to accept a direct chemical challenge or circuitry to mimic some pre-set response criteria. Therefore, the cost of developing lower cost sensors would remain relatively low. Such an approach would be predicated on a number of factors which the end user would not be able to control. These include: (1) assurance that a sufficient degree of vetted data from the reference source was available during the time period of interest, (2) the delay in acquiring the reference data and then applying it mathematically to the raw data could be substantial (days to months) and therefore the ability to use the lower cost sensor data as a quick screening tools would be hindered, (3) the end users would need the ability to obtain the reference data and then apply it correctly to normalize the raw response.

Summary Findings

It was obvious that there was no perfect option in developing a recommended calibration approach for low cost sensors. In fact, some felt strongly that a mixture of the three options might be required. Those involved in regulatory monitoring felt strongly that direct sensor calibration was mandated (option 2). Attendees who had some experience in use of a wireless calibration approach (option 1) indicated that it was not only feasible but was being done as part of one on-road fleet ozone monitoring program(3) . If one approach was viewed as the default method that could always be applied it was option #3. Normalization approaches are widely used (even in high grade research study designs) and would not require sensor developers to invest heavily in new hardware/software designs(4). Likewise, it would not require an investment in calibration signaling hardware/software from resource-limited air monitoring networks.

Many State and Federal air monitoring stations are starting to release continuous PM, and criteria gas air quality data in near real time via the internet. They are not currently sending out wireless based data which might be the source of the calibration signal defined by option #1. Local micro-environments are known to have a tremendous impact on PM concentrations, so sensor location when the calibration signal was being received could be an issue. O_3 concentrations are very homogeneous over wide spatial areas. If the sensor was away from traffic impacts (minimizing NO_2 and O_3 titration impacts) and outdoors (where it reacts with indoor surfaces), one could expect the ambient calibration point to be very useful in calibrating the sensor. $S0_2$ would seem to be a reasonable candidate for such a calibration approach and once again, measurements would need to be taken outdoors due to the infiltration loses observed between ambient and the indoor environment. Both CO and NO_2 represent microenvironmentally-sensitive gas pollutants (some degree of heterogeneity due to mobile source emissions). As such, there would need to be careful selection of an outdoor monitoring location for the single point method to be effective and not introduce serious bias into the resulting raw data collections.

After much discussion concerning option #2 and its technical feasibility, a simple question was asked of the breakout attendees. Would you purchase a calibration kit estimated to cost ~ $100 if the sensor it was to be used upon only cost $200? The answer was near unanimous- no! It made little economic sense to expect citizen scientists to purchase such kits at such a cost ratio and then have the technical ability to use them. Furthermore, sensor developers indicated they did not wish for such users to have the ability to reprogram response algorithms. As one sensor developer noted, “giving the user the ability to reprogram the response would result in only issues. If the sensor started reporting 'bad looking data' the user would automatically assume it was the device (and not the fact that a faulty calibration procedure had been performed)". Furthermore, multiple sensor developers indicated a more practical approach was to simply have the users send in the device for professional recalibration/refurbishment and that a known date of calibration expiration should be issued at the time of purchase. These certification dates should not exceed 1 year in length and in fact, many of the current mid-range sensor developers (<$5000) often indicate such certification periods. While attendees felt the electro-mechanical or circuit-based calibration (e.g., resistance) would work for some of the current sensor types, this approach gathered no traction in the discussions and was quickly dismissed as less likely to be developed by sensor developers.

The simplest of the mathematical models that might apply to an option #3 approach would be use of a linear equation relationship (y = mx +b) where the slope (m) and intercept (b) of the resulting raw versus reference data would be compared[5]. An equation like this is the primary means of establishing the degree of agreement between Federal Equivalency Monitors versus Federal Reference Monitors. The resulting slope and intercept are then used to re-establish the "true" response of the raw data. However, it must be recognized that many of the low cost sensors do not have a linear response (or may have a linear response for a specific range of their overall response curve. Therefore, it will never be a one size fits all approach and curve-linear relationship curves would need to be established. More importantly, the end users would have to be able to recognize that: (1) the data being compared was not of a linear nature, and (2) that one of the many various curve-linear models would have to be selected and then applied to the raw data. It would be expected that many lower cost sensor users would not have the technical ability to select the appropriate curve to apply. Likewise, end users having only modest technical backgrounds may balk at having to perform such efforts which would result in some degree of preventing them from reporting/using the raw data they have acquired. It was agreed that there would need to be some third party application (software) that would walk lower cost sensor users through raw data input, reference data input, appropriate curve selection, and ultimately recalculation of raw data its final form. No one was able to identify who should be responsible for such an application.

One approach that was not a part of the straw-man discussion but which was volunteered was "machine learning". This technique would use host-based processing of sensor data streams and mathematically (statistically) search out data values that appeared out of range. Data would be self-normalized (within the monitoring network) rather than any sensor calibration per se. It was agreed that such an approach, taken to its fullest potential, would eliminate the need for any of the straw-man options and help introduce "sanity checks" into overall data quality and probably represents the future of ubiquitous sensing data mining. One common concern about such an approach is that data viewed as abnormal (low or high) with respect to its peers, might in fact, be accurate and thus eliminated from use. Micro-environmental hot spots are known to exist (e.g., near road traffic emissions, combustion sources, etc) with widely fluctuating pollutant concentrations which would need to be considered in any machine learning application. Machine learning has been applied to large sensor networks involving such measurements as meteorological parameters(6). However, one would have to develop a systematic approach (infrastructure) for acquiring sensor data and then processing it. No such public or government infrastructure exists in the US. However, some European municipalities are involved in establishing such infrastructure and so the concept appears to be one more of economic rather than technical considerations(7).

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Table 1. Potential low cost sensor calibration options.

	Option 1	**Option 2**	**Option 3**
Key calibration feature	Wireless signal	Direct sensor calibration	Secondary data normalization
Panel ranking (option most preferable)	Low, but has been shown to be feasible	Highest for those involved in regulatory monitoring	High. Deemed most practical as it is already widely performed by professionals
Positive features	Calibrations could be performed on the go and take advantage of regulatory air monitoring station data	Ensures greatest level of confidence in data quality. Represents the traditional gold standard practice	Commonly performed among environmental professionals. Allows "sanity check" of data quality
Negative features	Monitoring stations would have to provide signal and sensors would have to have the means of receiving and using this signal	Economically less reasonable. Non-professionals probably not qualified to perform calibration procedures	Non-professionals may not know where to obtain verified data or how to normalize data using mathematical functions
Intangibles	Would require infrastructure to acquire and broadcast calibration signal	Sensor developers are limiting user access to calibration algorithms for practical reasons	An application could be developed that assisted novice users in data normalization but no lead for doing so currently exists
Likelihood of advancement	Doubtful infrastructure can be developed due to economic constraints	No impetus for developers to provide calibration kits. Sensors considered disposable	Likely. Only modest resources needed for a publically-available data normalization application