

Sensor Evaluation Report



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Abstract

This report summarizes the results of low cost air quality sensor performance trials conducted in the NERL's on-site laboratories located in Research Triangle Park, NC during 2012-2013. Such trials were viewed as highly valuable for all parties following the conclusion of the U.S. EPA's Air Sensor and APPs conference conducted in the spring of 2012. Conference attendees from a wide range of interests (government, sensor development, citizen scientists, etc) concluded that basic sensor performance characteristics of available sensor technologies were unknown. Many potential users of these technologies were unaware that data quality needed to be established or how one might perform such determinations. Many conference attendees shared that the U.S. EPA needed to take a leadership role to both educate sensor developers and end users about needed performance standards, share technical information about how one would establish such characteristics, and foster continuing dialogue between all interested parties on this subject matter.

As a result of the aforementioned conclusion, the U.S. EPA initiated a research program in the summer of 2012 to survey sensor developers about potential technology-sharing with the ultimate goal of conducting exhaustive laboratory-based sensor performance trials. Collaborating institutions responded to an open, web-based invitation to submit applications to participate. Applicant screening was performed that ensured the sensors being offered for evaluation were available to others for use and that they had not been previously examined via any third-party laboratory. In addition, there had to be a lack of publically-available information on sensor performance for inclusion in the research.

A total of nine institutions of multi-national origin agreed to establish confidential MCRADA research with the U.S. EPA associated with the performance of O₃ and NO₂ gas phase air quality sensors. These sensor types being selected due to their prevalence in the market place and the availability of established test regimens that might be applied. Findings associated with sensors shared by seven of these parties are described in this report and are being voluntarily shared here by the collaborating institutions. These institutions were a combination of academic, private sector, and non-profit organizations that had responded to the open challenge of participating in exhaustive laboratory-based trials of basic sensor performance characteristics.

Performance traits such as response linearity, response reaction times, detection limit, and response to interfering agents, among others were established. In addition, characteristics important to potential users such as battery life, ease of operation, data storage and/or communication protocols were investigated. Laboratory data was collected using an exposure chamber linked with either FRM or FEM instrumentation. Sensors were individually challenged using a variety of test conditions and their resulting response recorded. Replicate trials of each challenge were performed to provide needed statistical strength in establishing performance.

Select findings from these trials are as follows:

- (1) Many of these sensors, having commercial values of < \$1000, demonstrate some performance characteristics that often rival those of FRM/FEM instrumentation. The sensors often exhibited very fast response times with minimal rise and lag times which suggests potential use for continuous or near-continuous environmental monitoring.
- (2) Many of the sensors had a high degree of linearity over their full response range at concentrations often well above normally observed environmental concentrations.
- (3) While the sensors often did not have the detection limits as low as FRM/FEM instrumentation, they often achieved levels near these concentrations that would appear to meet a wide variety of environmentally-relevant monitoring needs.

- (4) Some of the sensors revealed some unwanted co-response to interfering agents (e.g., NO₂, O₃, SO₂). Likewise, extremes of RH and temperature often resulted in some undesirable response characteristics.
- (5) Establishment of data collection/recovery protocols involved a wide array of approaches to achieve success (e.g., WiFi hot spots, cellular telephone, SD card, proprietary web data portals). This often involved iterative upgrades to communication protocols, hardware and other integrated systems as testing was initiated on each device.

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Executive Summary

Background

Low cost air quality sensors are indicative of emerging technologies that have a wide appeal to both professional researchers and citizen scientists. They exist in numerous configurations (e.g., cell phone, hand-held) and are often available with a wide assortment of sensor configurations. Many of these configurations include the ability to measure gas phase air pollutants such as NO₂ and O₃. While the commercial availability of such devices has increased dramatically in the last five years, uncertainty about the quality of data such devices might be capable of providing has been raised.

Study Objectives

The U.S. EPA as part of its Air Climate & Energy (ACE) research program on emerging technologies (ACE EM-3), developed a research initiative that would seek to survey both NO₂ and O₃ low cost sensors as to their availability and then work in collaboration with their developers on understanding basic performance characteristics of such sensors. A world-wide survey of potential sensor candidates for laboratory-based evaluations was conducted. Applicant sensors were screened for inclusion in the research based upon publicized selection criteria. Evaluation of each application by the U.S. EPA's Federal Technology Transfer Act (FTTA) office was performed to ensure the integrity of the collaborative agreement and the confidential nature of technology-sharing. As a result, a total of nine Material Cooperative Research and Development Agreements (MCRADAs) were established during the 2012-2013 time period where sensor developers submitted their technologies to the U.S. EPA for exhaustive laboratory trials. The work would be collaborative in nature between the U.S. EPA and the various institutions but confidential in that findings and proprietary information related to sensor design and performance would not be shared outside of the one-on-one MCRADA relationship. The aforementioned trials would be performed at near-Federal Reference and Equivalent Method (FRM/FEM) criteria in U.S. EPA's Research Triangle Park, NC laboratories. The comparison of performance as it related to this very high level of data quality was conducted to provide the greatest amount of feedback possible to the sensor developers as to the value of their device for a wide range of air quality applications.

Study Approach

Collaborative research was initiated during the fall of 2012 and was completed by the summer 2013. The U.S. EPA's existing FRM/FEM laboratory was modified to accommodate sensor testing. A quality assurance program was designed and instituted that featured definitive operating procedures for all reference monitors, gas generation systems, test chamber operating parameters, sensor operation, and data recovery/analysis procedures. Sensors were received by the U.S. EPA and integrated into the established testing regimen agreed upon by all parties. Third party (external to the study investigators) quality assurance audits were performed during the study period to ensure data collection procedures met all established protocols. An iterative process of dialogue was maintained by all parties during this time period featuring both group (all MCRADA collaborators) as well as individual communication between the U.S. EPA and any respective institution to ensure full disclosure of the research protocol, progress, difficulties, and achievements that occurred as a result of the collaboration.

Following the completion of the data collection, validation, and analysis, a summary report was provided to each MCRADA institution as to the basic performance characteristics of their sensor(s). Such feedback included but was not limited to data on response time, response linearity, influence of interfering agents and ease of use. The feedback provided to each collaborator was defined by numerous factors such as already established inability of the sensor to operate under certain test conditions (e.g. extremes of temperature, relative humidity); inclusion in a specific testing regimen when pre-test indicated it would not be fruitful; and lastly, but equally important, the availability of U.S. EPA resources to conduct this research. The U.S. EPA was committed to provide some feedback to all parties concerning performance and therefore decisions were made in the execution of the test regimen to best balance resources versus time expended with each sensor.

Sensor Performance Results

Discreet statistical evaluation of sensor performance was provided to each sensor developer as well as ancillary information pertaining to ease of use features. Each sensor tested had unique qualities of both the discreet as well as ease of use features.

Ease of Use Features Evaluation

Concerning ancillary information pertaining to ease of use features, several key findings were evident. In general these included but not limited to:

- *Power Requirements:* Battery capability varied widely between sensors. Li-Ion and other rechargeable media types were common features. Operating times of as short as 4 hours and >24 hrs were evident or reported by the sensor developers. In order to ensure successful testing of the sensors using the lengthy and often automated procedures, direct line voltage was provided to each sensor to ensure their effective operation and data integrity.
- *Data collection/transmission/storage/recovery:* There were numerous data collection/transmission/storage/recovery approaches observed between the various sensor devices. Therefore, extensive efforts had to be performed to ensure data recovery to perform the evaluations. Cellular communication, WiFi hot spots, direct storage via laptops, electronic tablets, and even third party (proprietary web hosting) protocols had to be established, developed, or in some cases unexpectedly refined as to the manufacturer's suggested protocols. Data communication issues had to be fully vetted to ensure both consistent and reliable data recovery.
- *Data Schemes:* Data schema was widely variable between the sensors evaluated. There currently is no standardized approach for how data is communicated and the unique pattern of data formatting (and the types of data being reported) makes evaluations complicated. Individual data recovery programs had to be established for each sensor so that data could be recovered and the U.S. EPA had sufficient knowledge of what data values were actually being reported. As an example, some sensors directly reported an estimation of gas concentration whereas others might only report a variable (e.g., change in resistance, voltage) that needed to be translated using either an EPA-derived algorithm or preferably one provided by the manufacturer to allow raw data to be reported as a concentration estimate.
- *Response Range:* Response range of the sensors varied widely. While some sensors exhibited detection limits of < 10 ppb, others responded more favorably to higher concentrations at the ppm level. The testing protocol was not changed because of these differences but the variance in response when supposedly very similar gas detection

mechanisms were being employed by the sensors may indicate that the processing of raw signal is a vital part of ensuring their overall utility.

Sensor Performance Characteristics

Many of the sensors tested exhibited qualities (e.g., response times, detection limits) rivaling those of expensive FRM/FEM instrumentation. For example, it was not unusual to see response times well under 1 minute with small rise and lag times following known changes in challenge conditions. Some of these results are summarized below with more detailed descriptions in Section 5:

- *Precision*: All of the sensors tested provided good to excellent precision - their ability to reproduce a response at given challenge concentrations. It was not usual to see relative standard deviations of response under 10% at both the low (near 0 ppb) and high (>200 ppb) test conditions.
- *Linearity*: The sensors exhibited excellent linearity over a wide range of challenge concentrations (0 to >200 to 500 ppb; the latter being dependent on the individual sensor and gas). Coefficients of determination greater than 0.95 were often achieved.
- *Relative Humidity and Temperature Changes*: There was wide disparity in the response of individual sensors to extremes of either RH or temperature challenge. Both minimal impacts as well as extreme impacts were observed as they relate to the sensors successfully reporting the challenge concentrations as environmental conditions changed. Some of this was expected due to the very nature of the sensing mechanism (approach) often employed in low cost sensors. Metal oxide and other electrochemical sensing membranes have physical properties that need relatively stable operating parameters to remain effective. A number of the sensors failed under such challenge circumstances with data responses outside of acceptable reporting parameters. Resources were not available to allow for gradual changes in environmental conditions under varying challenge gas concentrations and therefore, the full scope of impact of changes in RH and temperature cannot be established.
- *Interferences*: Wide capabilities of the sensors to respond favorably (minimally) to the presence of a co-pollutant were observed. Some produced an interfering response of < 3 ppb while others reported values that exceeded the ability of the sensors themselves to report an output. Mixtures of either O₃, NO₂ or SO₂ were used in various combinations of these test challenges. Challenge concentrations of the interfering agent were established at a single, relatively high environmental concentration that one might consider as a “worst case” scenario. Therefore, the evaluations reported here merely provide a basic understanding of whether a sensor might or might not (in its test configuration) be susceptible to interferences.

Conclusions

This summary should indicate that while both the discreet (performance characteristics) and ease of use characteristics of each device were highly variable, there is strong evidence that the sensors tested have immediate use for a wide array of environmental applications. In fact, the overall pattern of performance for a given trait often rivaled (sometimes exceeded) that of the FRM/FEM instrumentation while costing 2 to 4 orders of magnitude less in comparison. Citizen scientists, academics, and others needing to obtain informative air quality data should not discount the value in employing such devices to gain a general understanding of local air quality. That being said, the issues observed with the sensors relating to communication protocols, data storage, response range, environmental conditions, and specificity of response,

among others, should not be discounted by potential end users. The information provided to the collaborating institutions on sensor performance and which is summarized in this report, represents a first step in helping to ensure the next generation of low cost air quality sensors being developed have even more capabilities to meet a wide variety of air quality monitoring needs. It also provides potential low cost sensor users with key information they need about sensor performance and the criteria they need to understand in executing successful data collection.

Abbreviations

AC	Alternating Current
ACE	Air, Climate, and Energy
ASAP	EPA's Air Sensor and APPs sensor conference
°C	Degrees Celsius
CFR	Code of Federal Regulations
cm	Centimeter
cm s ⁻¹	Centimeters per Second
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DC	Direct Current
EM	Emerging Technology
FEM	Federal Equivalent Method
FRM	Federal Reference Method
FTTA	Federal Technology Transfer Act
hr	Hour
IDL	Instrument Detection Limit
IE	Interference Equivalent
in	Inch
kOhm	Kilo Ohm
LC	Liquid Crystal
LCD	Liquid Crystal Display
LDL	Lower Detectable Limit
Li-ion	Lithium Ion
Li-Po	Lithium Ion Polymer
MCRADA	Material Cooperative Research and Development Agreement
min	Minute
mL	Milliliter
MOS	Metal Oxide Sensors
mV	Millivolts
NA	Not Applicable
NDIR	Nondispersive Infrared
NERL	National Exposure Research Laboratory
NIST	National Institute of Standards and Technology
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Generic term for mono-nitrogen oxides
O ₃	Ozone
OD	Outer Diameter
ORD	Office of Research and Development
PC	Personal Computer
PFA	Perfluoroalkoxy
PID	Photoionization Detector
ppb	Parts Per Billion
ppm	Parts Per Million
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/ Quality Control
RH	Relative Humidity
ROP	Research Operating Procedure

RTD	Resistive Temperature Device
S	Standard Deviation
SD	Secure Digital
SIM	Subscriber Identity Module
SO ₂	Sulfur Dioxide
SOP	Standard Operating Procedure
µm	Micrometer
URL	Upper Range Limit
USB	Universal Serial Bus
U.S. EPA	United States Environmental Protection Agency
UV	Ultraviolet
V	Volt
VOC	Volatile Organic Compound

1. Introduction

1.1 Background

The U.S. EPA's Apps & Sensors for Air Pollution (ASAP) meeting conducted in the spring of 2012 resulted in more than 80 invited participants from a wide variety of backgrounds to discuss the state of sensor technology. Such technologies are being described in the scientific literature and their general availability for air quality monitoring is being evaluated.^{1,2,3,4} During the meeting, general discussions on the availability of various sensors were reported as well as how they were (or potentially could be) integrated into environmental air quality research. Following the completion of this meeting, the U.S. EPA summarized key findings.⁵ One such finding was the uncertainty of data quality associated with low cost sensor technologies. It was apparent that much attention had been given by sensor developers in the development of devices that met criteria such as:

- Low cost.
- Lightweight and of small physical size (often cell phone size).
- Requiring minimal user knowledge or training to initiate data collection.
- Providing continuous or near-continuous pollutant data estimations.
- Reporting data either directly on the device or through some web-based portal.
- Utilizing emerging technologies such as Metal Oxide Sensors (MOS) theorized as having a high degree of potential as a sensing element.

It was also apparent that little attention had actually been given to understanding the data quality being produced by this class of air quality monitors. Often sensor developers were relying upon sensor element manufacturers (the base technology that low cost sensors were being designed around) to provide estimates of performance to the general public and potential end users. This was being done not as a result of lax attitudes towards data quality assurance issues but rather often a genuine lack of knowledge about what performance measures were important. Likewise, low cost sensor developers often did not have the capability of scientifically investigating this issue due to either lack of technical expertise or availability of proper testing facilities. One recommendation, established as an action item for those in attending the 2012 ASAP meeting, was to develop a better understanding of basic sensor performance characteristics and continue the dialogue between all parties (sensor developers, citizens, community action groups, academics, and regulatory officials, and scientific investigators-at-large).

As a direct result of the aforementioned recommendation, the U.S. EPA began an internal dialogue about how best to facilitate the exchange of information on basic sensor

¹ Roadmap for Next Generation Air Monitoring- U.S. Environmental Protection Agency. <http://www.epa.gov/research/airscience/docs/roadmap-20130308.pdf>. March 8, 2013.

² Snyder, E., Watkins, T., Thoma, E., Williams, R., Solomon, P., Hagler, G., Shelow, D., Hindin, D., Kilaru, V., Preuss, P. Changing the paradigm for air pollution monitoring. *Environmental Science and Technology*, 47: 11369-11377 (2013).

³ White, R., Paprotny, I., Doering, F., Cascio, W., Solomon, P., Gundel, L. Sensors and "Apps" for Community-Based Atmospheric Monitoring. *Environmental Manager*. May 2012. 36-46 (2012).

⁴ Hall ES, Kaushik SM, Vanderpool RW, Duvall RM, Beaver MR, Long RW, and Solomon PA. Integrating Air Pollution Sensors into Current Ambient Air Monitoring Networks: Practical Considerations, *American Journal of Environmental Engineering*, (in press 2014).

⁵ Vallano, D., Snyder, E., Kilaru, V., Thoma, E., Williams, R., Hagler, G., Watkins, T. Air Pollution Sensors. Highlights from an EPA workshop on the evolution and revolution in low cost participatory air monitoring. *Environmental Manager*. December 2012. 28-33 (2012).

performance and how to share that information with those at the cutting edge of low cost sensor development. Such an endeavor might provide both immediate as well as long-term benefit to all parties. In particular, the U.S. EPA might be in position to help facilitate improved low cost sensor performance in this highly evolving area by sharing expertise in air quality monitoring. In doing so, one might forecast faster development of improved air quality sensors, or a better understanding of the capabilities of these devices being made readily available to the general public.

1.2 Research Initiative

The U.S. EPA as part of its ACE research portfolio had an established program focusing upon emerging technologies.⁶ Low cost sensor technology was an area of growing interest. Based upon the recommendations of the ASAP 2012 and those associated with the ACE EM-3 research area (Emerging Technology), a research initiative was proposed that would integrate the following components:

- Continue the dialogue between sensor developers and the U.S. EPA on sensor performance.
- Perform a market survey of low cost sensors associated with gas phase measurement of NO₂ and O₃.
- Develop laboratory facilities and protocols that would be needed to evaluate such sensors for basic performance characteristics.
- Establish a communication strategy for engaging sensor developers about the planned laboratory research, and
- Seek out and then establish collaborative research agreements between the U.S. EPA and interested sensor developers.

1.3 Call for Sensor Developer Applications

The U.S. EPA established a world-wide open call for sensor developers to submit an application for inclusion in this research (<http://www.epa.gov/airscience/air-sensor.htm>). Interested parties were requested to submit a statement of interest by June 30, 2012 and provide basic information about their device. Interested parties were informed that due to capacity constraints (resources), only a limited number of each sensor type would be accepted for evaluation and that the scope of the evaluation would be limited to a practical (environmentally-relevant) range of pollutant concentrations and environmental conditions (e.g. humidity and potential interferences). Institutions submitting applications were informed that they be invited to visit the U.S. EPA laboratories where the work would be conducted in the fall of 2013 to discuss their instruments, the evaluation protocol, and receive a tour of the facility. Applicants agreeing to the terms of the collaboration would receive information on the performance of their device under known environmental conditions. Applicant's sensors were asked to meet the following criteria:

- Technical feasibility to measure NO₂ and/or O₃ at environmentally relevant concentrations.
- Developers had at least some basic knowledge about their device's expected performance characteristics that would minimize testing devices under disadvantageous circumstances where the device might be damaged.
- No previous standardized evaluations under known challenge test conditions by any party.

⁶ Snyder, E., Watkins, T., Thoma, E., Williams, R., Solomon, P., Hagler, G., Shelow, D., Hindin, D., Kilaru, V., Preuss, P. Changing the paradigm for air pollution monitoring. *Environmental Science and Technology*, 47: 11369-11377 (2013).

- Represent highly portable sensor and smart phone type applications featuring continuous measurement capabilities.

1.4 Study Inclusion Criteria

The evaluation offered to applicants was intended to provide technical feedback to developers of newer, low cost personal/portable sensors. It would not represent any U.S. EPA endorsement of any device evaluated. The device would need to be fully operational at its time of delivery and be at a development stage where it had its own power supply and telecommunication tools (if applicable). The U.S. EPA requested that each applicant approved for study inclusion:

- Provide clear, written, step-wise directions for operating the device (set-up/operation/data recovery, etc) at its point of release to the US EPA. If such operating procedures were not developed, they had to be agreeable to working quickly with the U.S. EPA on such documentation.
- Provide access to the device for at least two months during the evaluation period.
- Provide self-powered devices capable of operation using internal (battery) power (either replacement cells or rechargeable cells) and that if at all possible, it would need to operate at a minimum of eight hours on internal power. If the device requires AC power for operation, applicants were required to provide the necessary electrical transformer/connections.
- Provide a device housed within a break-resistant case or have its own external cover to permit normal handling practices.
- Provide a device capable of accepting a wide range of expected temperature and relative humidity conditions during testing and pose no intrinsic safety issues.

1.5 Collaborative Research Agreement

A total of nine applicants submitted proposals to join in the collaboration. Each of these applicant's proposals were then thoroughly reviewed by the U.S. EPA technical staff as well as officials associated with the FTTA to ensure applicable adherence to collaborative research standards and confidential nature of the technology to be shared between parties. Applicants were invited to the U.S. EPA'S Research Triangle Park, NC campus in October 2012 to tour the facilities, discuss the technical nature of the proposed research, and to gain a fuller understanding about the purpose of the collaboration and share their perspective about its potential (<http://www.epa.gov/nerl/features/sensors.html>). Following this event, all nine of the proposed applicants agreed to the formal collaborative (confidential) research with signatories associated with each institution acknowledging the establishment of the MCRADAS. The research reported here represents the first use of such agreements involving innovative technology sharing between the U.S. EPA and various institutions.

The names of the collaborating MCRADA institutions and the findings reported in this report represent the release on previously confidential and collaborative research data. Each collaborating institution named in this report and technical information about their sensor and its performance have agreed to public data sharing in a spirit of advancing sensor technology as a whole and informing potential end users about the value and limitations of such current technologies. This public data sharing was not a component of the MCRADA requirements and the institutions providing this information are applauded for their willingness to share this information with others.

2. Study Objectives

2.1 Primary Goals

To address the issues discussed in the ASAP 2012 meeting, the U.S. EPA conducted an Air Sensor/Application Evaluation and collaboration challenge. This challenge was viewed as a high priority need for the U.S. EPA and one in which the NERL was asked to take a leadership role in promoting. The NERL therefore sought out novel sensor technologies for the measurement of ambient NO₂ and O₃ through a general appeal to inventors as discussed earlier. These sensor types being selected due to their prevalence in the market place and the availability of established test regimens that might be applied. The technology provided by the Collaborator was temporarily transferred to the NERL where its performance was examined under controlled laboratory conditions. The purpose of this collaboration was to provide the NERL an opportunity to examine the emerging area of sensor technologies and to share technical feedback to the Collaborator on the general performance characteristics of their particular sensor as a means of advancing the general state-of-the-science.

2.2 Laboratory Testing

The NERL provided laboratory space, technical staffing, test atmosphere generation equipment and reference analyzers for the research described below. Laboratory-based research was initiated in October 2012 and completed in July 2013. The obtained data was validated, tabulated and then summarized with a preliminary report on the sensor's general performance characteristics produced during the summer 2013 and then shared with the Collaborator for comment. A final report was provided to each collaborator in October 2013 following review by all parties and iterative co-development.

2.3 Specific Objectives

To achieve the primary goals discussed above, the specific objectives were to:

- Evaluate each transferred sensor being tested under known laboratory/chamber conditions including relative humidity, temperature, pollutant challenge atmosphere and interfering species concentration (e.g., NO₂).
- Establish evaluation criteria for each device including: (a) linearity of response; (b) precision at each known reference concentration; (c) determination of the lowest established concentration in which a response was detected, (d) concentration resolution, (e) response time, and (f) suggested range of operation to achieve best practical operation conditions. The specifics of each criteria discussed above are defined in detail in the Study Approach section of this report. Replicate trials were performed as a means to ensure data quality.
- Summarize data findings for a report detailing basic performance characteristic of each sensor. These findings would describe not only how well a given sensor performed with respect to a given challenge (e.g., response time), but also more generalized findings about end user consideration. Of these, such topics as its ease of use were hoped to be defined.

2.4 Secondary Goal Objectives

The aforementioned objectives were defined prior to the initiation of the collaborative research. However, other secondary objectives became quickly evident as sensors were received by the U.S. EPA and laboratory work was initiated. These secondary (but no less important) objectives that needed to be achieved included:

- *Development of more refined SOPs for many of the sensors to ensure the accurate operation of the device and ensure data quality meeting the unique U.S. EPA Quality Assurance Project Plan (QAPP) developed for this research.* Each collaborating institution reviewed and contributed to the QAPP prior to initiation of any data collection. While sensor developers had some operating procedures in hand which they shared with the U.S. EPA, they sometimes lacked sufficient details (e.g., photos, figures, guidelines) that instructed the end user. This objective had to be achieved before QAPP-approved data could be collected.
- *Refinement of communication or data/storage/gathering protocols.* It was expected that data recovery would be easily achieved since the sensors associated with this research were available for others to use. However, each of the devices tested as part of this research often had very unique protocols for how data was being gathered and communicated by the device. Review of the SOPs revealed a wide range of needed systems to ensure timely and secure data recovery. Some sensors stored data internally on SD cards, some directly transmitted data to tablets or PCs. Other sensors used a variety of wireless communication protocols (e.g., specific SIM card for cellular transmissions, local WiFi, Bluetooth, proprietary website hosting). All of these protocols had to be considered in executing the study approach and building up the necessary infrastructure to support the research. In some cases, multiple iterations of either hardware or software had to be developed by both parties (U.S. EPA/collaborating institution) to ensure data storage/recovery.
- *Identification of sensor power requirements.* The ability of the sensors to provide internal power supplies (battery) sufficient to allow extended automated exposure chamber testing was often lacking upon initial testing. Extended operations in the 12 to 24 hr range was viewed as necessary to ensure replication of test conditions and efficient data collection. Consequently, the sensor devices had to be re-wired from an internal power source to a direct line source. This required working with sensor developers on the needed voltage and circuit connections. In many cases, sensor developers provided direct wiring harnesses that met this need.

3. Study Approach

3.1 Background

As previously stated, one goal of this effort was to develop an understanding of what technology might prove valuable in conducting the next generation of air monitoring. Upon their discovery, such technologies were obtained in collaboration with inventors as well as commercial and research organizations and examined under controlled laboratory conditions. If found to be acceptable, devices might be recommended for incorporation in the next phase of testing, short pilot studies involving direct environmental monitoring and comparison to collocated reference methods.

The following evaluation criteria were established for each candidate sensor technology: (1) linearity of response (range), (2) precision of measurements, (3) lowest established concentration in which a response was detected (lower detectable limit [LDL]), (4) concentration resolution, (5) response time, (6) interference equivalents, and (7) relative humidity (RH) and temperature influences. This manuscript describes the experimental systems required to assess the performance of such technologies.

3.2 Evaluation Procedures

3.2.1 Exposure Chamber

The exposure chamber (Ace Glassware) shown in Figure 1 was designed and constructed for the evaluation testing. The internal diameter and length of the glass chamber were large enough (15.2 cm X 91.4 cm) to accommodate at least one or more of the test sensors. The chamber had four sampling ports spaced 3.8 cm apart. Reference analyzer sample lines and sensor signal and power supply lines passed through Teflon-lined fitting caps into the exposure chamber. Unused port positions were filled with solid Teflon plugs so that laboratory air would not dilute the generated test atmosphere. Reference analyzer sampling lines were made of 6.4-mm (0.25-in.) outer diameter (OD) perfluoroalkoxy (PFA) Teflon. Particulate filters (5- μ m pore size) were fitted to each reference analyzer's inlet port. Air containing known concentrations of the test atmosphere and/or interferences gas was provided to the chamber inlet as needed to conduct the established protocols. An exhaust line was attached to the chamber outlet and placed into the laboratory's 6-in. ceiling vent to allow a continuous flow through design feature.

3.2.2 Physical Parameters (Temperature and Relative Humidity)

Temperature within the exposure chamber was controlled through the use of the shelter's HVAC system and supplemented with heating pads and dry ice to obtain test conditions. RH within the exposure chamber was controlled through the use of a de-ionized water bubbler. Temperature and RH were measured with a temperature/RH probe designed by Alion. The temperature sensor consists of a precision thin-film platinum 1000- Ω resistive temperature device (RTD) that employs a linear resistance change with temperature converted to a 0–10 V DC output proportional to 0–100.0 °C. The sensor is calibrated (zero and span) using a NIST-traceable reference thermometer. The RH sensor consists of a HyCal, Inc. IH-3602-C monolithic integrated circuit capacitance sensor that produces a linear voltage proportional to RH (0–10 V DC output directly proportional to 0–100% RH). The RH sensor is calibrated using saturated salt solutions that have known RH over head space.

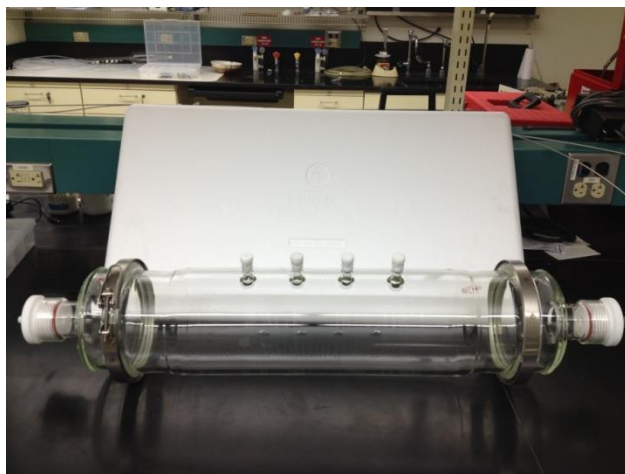


Figure 1. Ace Glassware Exposure Chamber Showing Input and Output Ports and Caps

The temperature and RH signal response are shown on a liquid crystal display (LCD). Both sensors share a common probe that was inserted into one of the ports of the sampling manifold, typically at the end of the series of ports to lessen the chance of contamination from the probe's stainless steel composition. The RH measurements require a minimal face velocity of 10 cm s^{-1} to be accurate. The analog output signals that correspond to the temperature and RH signals were recorded by the data acquisition system during each experiment. Test atmospheres were established using an NIST-traceable and programmable gas delivery system (Teledyne API Model T700U) with constituents delivered to the system from either EPA reference gas standards (SO_2 , NO_2) or independent generation device (O_3). Dilution air that had been scrubbed of particulate matter, moisture, and hydrocarbons was delivered to the mixing system to meet test gas dilution and chamber flow through needs.

3.2.3 Continuous Gas (Reference) Monitors

Samples for the continuous reference analyzers ($\text{NO}/\text{NO}_2/\text{NO}_x$, O_3 , and SO_2) were drawn to the monitors through the previously described sample ports and PFA lines at flow rates from 500 to 1000 mL/min. Flow measurements were taken at the beginning of each test run to ensure the total sampling flow requirements of the instruments did not exceed that of the source atmosphere introduced into the sampling manifold during the test. The continuous analyzers used in this study are given in Table 1.

Table 1. Reference Analyzers Used in Sensor Evaluation Study

Pollutant	Analyzer	Principle of Operation
NO_2	Thermo Model 42C $\text{NO}/\text{NO}_2/\text{NO}_x$ Analyzer	O_3 -chemiluminescence
O_3	2B Model 205 O_3 Analyzer	UV Absorption
SO_2	Thermo Model 43C SO_2 Analyzer	Pulsed Fluorescence

The operating procedure for the NO₂ analyzers is based on the NO₂ Federal Reference Method (FRM)⁷ and recommendations given in the manufacturer's operator's manual. Likewise, the operating procedure for the SO₂ analyzers is based on the SO₂ FRM⁸ and recommendations given in the manufacturer's operator's manual. The operating procedure for the UV O₃ analyzers (a Federal Equivalent Method [FEM]⁹) is based on the standard EPA ambient measurements of O₃ and recommendations given in the manufacturer's operator's manual. Data from the reference analyzers and a temperature and humidity monitor were continuously recorded by the data acquisition system. The sensors' data were transmitted either by Blue Tooth or USB/RS-232 directly to their special application software or smart phone applications. The date, time, and results of each novel sensor test were documented.

3.2.4 System Characterization

Prior to initiating the sensor tests, the overall system was evaluated through a series of experiments. The results of these characterization runs indicated the system was capable of obtaining and maintaining (over a multiple day period) a temperature range of <5 °C->45 °C. In addition, RH control in the range of 20% to near 100% was achieved. It was also determined that the system residence time (amount of time it takes for a change in a system parameter to be recorded by the corresponding reference instrument) was less than 5 minutes.

3.2.5 Sensor under Test Samples

The sensor(s) undergoing testing was placed inside the glass exposure chamber after following start-up procedures found in either a standard operating procedure (SOP) or research operating procedure (ROP) provided by each participating organization. Samples were drawn to the reference monitor through a sample pump/fan located inside the instrument or by exposure of its internal sensor to the chamber atmosphere. Positioning (orientation) of the sensor in the test chamber was defined by the manufacturer to ensure representative data collections under normal operating procedures. A list of the quality assurance procedures used in the execution of this effort are reported in Appendix C.

3.3 Test Procedures

The following evaluation criteria were established for each device under each test condition: (1) linearity of response (range), (2) precision of measurements, (3) lowest established concentration in which a response was detected (lower detectable limit [LDL]), (4) concentration resolution, (5) response time, (6) interference equivalents, and (7) RH and temperature influences. A minimum of two RH conditions (e.g., dry air ≤ 25% RH, humid air ≥ 85% RH) were incorporated into the evaluation runs as well as a minimum of two temperature ranges (e.g., low near 0 °C, high ≥ 50 °C).

3.3.1 Linearity (Range)

Definition: Nominal minimum and maximum concentrations that a method is capable of measuring.

⁷ 40 CFR Part 50 Appendix F - Measurement Principle and Calibration Procedure for the Measurement of Nitrogen Dioxide in the Atmosphere (Gas Phase Chemiluminescence)

⁸ 40 CFR Part 50 Appendix A-1 - Measurement Principle and Calibration Procedure for the Measurement of Sulfur Dioxide in the Atmosphere (Ultraviolet Pulsed Fluorescence Method)

⁹ 2B Technologies Model 202 and 205 Ozone Monitors- Automated Equivalent Method: EQOA-0410-190 Federal Register: Vol.75, pages 22126-22127, 04/27/2010

Test procedure: Determine a suitable calibration curve showing the test analyzer's measurement response over at least 95% of the required or indicated measurement range (e.g., 0–500 ppb).

3.3.2 Precision of Measurements

Definition: Variation about the mean of repeated measurements of the same pollutant concentration, expressed as 1 standard deviation.

Test procedure: Precision of measurements was evaluated by conducting three replicates: (1) Sample test atmosphere A₀ (zero air). (2) Measure test atmosphere, A_p, and record the stable reading (in ppb) as P₁. (3) Repeat the second step two more times, record values for P₂ and P₃ after each test, and calculate precision (P) as follows:

$$P = \sqrt{\frac{1}{2} \left[\sum_{i=1}^3 P_i^2 - \frac{1}{3} \left(\sum_{i=1}^3 P_i \right)^2 \right]}$$

3.3.3 Lower Detectable Limit (LDL)

Definition: Minimum pollutant concentration that produces a measurement or measurement output signal of at least twice the noise level.

Test procedure: Measure zero air and record the stable measurement reading in ppb as B_Z. Generate and measure a pollutant test concentration equal to the value for the lower detectable limit specified in Table B–1 to Subpart B of Part 53 (table shown in Appendix A of this report). Record the test analyzer's stable measurement reading (in ppb) as B_L. Determine the LDL test result as LDL = B_L – B_Z.

3.3.4 Concentration Resolution

Definition: Smallest amount of input signal change that the instrument can detect reliably. This term is determined by the instrument *noise*. Noise is the spontaneous, short-duration deviations in measurements or measurement signal output about the mean output that are not caused by input concentration changes. Measurement noise is determined as the standard deviation (S) of a series of measurements of a constant concentration about the mean and is expressed in concentration units.

Test procedure: (1) Measure zero air with the test analyzer. Record 10 test analyzer concentration measurements with at least 2 minutes separating successive measurements. Label and record the test measurements as r₁, r₂, r₃, . . . r_i, . . . r₁₀. (2) Repeat step 1 using a pollutant test atmosphere 80% of the upper range limit (URL). Calculate S₀ and S₈₀ as follows:

$$S = \sqrt{\frac{1}{n-1} \left[\sum_{i=1}^{10} r_i^2 - \frac{1}{n} \left(\sum_{i=1}^{10} r_i \right)^2 \right]}$$

3.3.5 Response Time

3.3.5.1 Lag Time

Definition: Time interval between a step change in input concentration and the first observable corresponding change in measurement response.

Test procedure: Determine the elapsed time between the change in test concentration from zero air to 80% URL and the first observable (two times the noise level) measurement response.

3.3.5.2 Rise Time

Definition: Time interval between initial measurement response and 95% of final response after a step increase in input concentration.

Test procedure: Calculate 95% of the measurement reading and determine the elapsed time between the first observable (two times noise level) measurement response and a response equal to 95% of the reading.

3.3.6 Interference Equivalent

Definition: Positive or negative measurement response caused by a substance other than the one being measured.

Test procedure: (1) Sample and measure test atmosphere zero air. Allow for a stable measurement reading and record the reading as R (in ppb). (2) Sample and measure the interferent test atmosphere and record the stable reading in ppb as R_i . (3) Calculate the interference equivalent (IE) as $IE = R_i - R$.

The test analyzers were challenged, in turn, with each potential interfering agent (interferent) specified in Table 2 at a concentration substantially higher than that likely to be found in the ambient air.

Table 2. Interference Test Atmospheres for Apps/Sensors

Interferent	Concentration (ppb)
O₃ Sensors	
SO ₂	>200
NO ₂	>200
NO₂ Sensors	
SO ₂	>200
O ₃	>200
NO	>200

3.3.7 Relative Humidity and Temperature Influences

3.3.7.1 Relative Humidity (RH)

Test procedure: Determine response to a known test concentration under dry (RH < 25%) and high humidity (RH > 85%) conditions.

3.3.7.2 Temperature

Test procedure: Determine response to a known test concentration under low (near 0 °C) and high (≥ 50 °C) temperature conditions.

4. Quality Assurance

4.1 Development of QA/QC Materials

The U.S. EPA conducted all of the research presented in this report through an integrated program of Quality Assurance/Quality Control (QA/QC) activities. Principals of each major QA/QC activity are defined below. Quality assurance protocols were co-developed between the U.S. EPA and the sensor developers. The documents had to be crafted so that trained technicians knowledgeable about general air quality instrumentation procedures could operate the devices and that non-trained QA representatives fully understood the intent of each protocol. In other words, the SOPs had to be written so that others, even those not associated with the immediate work but who had some scientific background, could understand how to operate the devices. SOPs were developed, reviewed and ultimately approved by multiple U.S. EPA staff members including the representative NERL Quality Assurance Manager.

The aforementioned SOPs were but one component of an U.S. EPA Quality Assurance Project Plan (QAPP; NERL-QAPP-AB-12-03) entitled "ORD Sensor/Application test bed challenge: Investigation of apps/sensors response under controlled laboratory conditions." The QAPP defined such practical guidelines as defining those who would be involved in the research (e.g., named U.S. EPA, Alion Scientific contract staff, sensor development collaborators), data quality objectives (those that could be defined as in many cases the basic performance characteristics of the device was unknown for a given area); the programs to be employed to ensure successful data collection/storage and integrity; data generation and analytical methods to be employed (especially with respect to the utilization of FRM and FEM collocated monitor and test chamber characterization); statistical treatment of collected data; and parties responsible for overall project and data management. A full listing of relevant QA documentation is provided in Appendix C.

4.2 Data Collection

Specifics of the study approach and how replicate data collections were used to address data collection measurement uncertainty is defined elsewhere. At a minimum, replicates were typically performed at least twice for each challenge condition and in the vast majority of cases these were performed in triplicate. Laboratory and electronic notebook entries were made simultaneously with each data collection event to fully document the test conditions. Digital photographs were obtained showing each sensor in the test chamber and how it was positioned to document its vertical and horizontal physicality. Raw data was processed following its transfer into Microsoft Excel (v 2007). Second party review of data collection/transfer, record keeping, as well as the summary data analyses performed using this software was performed through trained QA staff (Alion Science and Technology).

4.3 QA Systems Audit

In addition to the QA oversight described immediately above, a formal QA systems audit was performed by the NERL's QA Manager in January 2013. This audit involved an in-person inspection of the test facility, the FRM/FEM instrumentation procedures being used to compare individual sensor response, observance of actual sensor challenge operations and adherence to SOPs/ROPs and specific QAPP requirements. Findings from the system audit indicated a high degree of compliance with all SOPs/ROPs and QAPP requirements. A recommendation was made that more extensive written documentation of daily test conditions in the laboratory

notebook be performed which would be advantageous to the project and which would supplement the electronic records already being obtained. The recommendation was immediately implemented. This was not a negative finding but rather one which the auditor indicated would minimize any future issue with describing test conditions and if needed, provide the means to more easily reproduce the work.

4.4 Data Inclusion Process

Following the completion of data collection and its summarization, all of the MCRADA collaborators received full copies of the raw data used to summarize findings relating to their specific sensors. Data inclusion criteria were defined (revisited) and if for any reason data were voided or excluded from inclusion the reason for such events were described. Sensor developers were asked to review the statistical findings (tabular and graphical representations) and approve the results as being fully representative of meeting the study objectives and performance characteristic definitions established in the Study Approach and QAPP. Collaborators were requested to provide alternative and other complimentary data analyses using the raw data provided. Only one such event occurred. Review of the raw data from one collaborator resulted in what was previously considered to be a negative integer (negative concentration) in the raw data output and which was actually a delimiter and not defined to the U.S. EPA prior to initiation of the data collection as non-value column descriptor. The collaboration institution summarily performed the needed statistical calculations and graphics development to correctly report findings associated with that given sensor treatment.

5. Sensor Description, Results and Discussion

The specifications of each sensor evaluated in this challenge are summarized in detail in Table 14. While some sensors had the capability to measure multiple pollutants, only NO₂ and O₃ measurements and performance criteria were evaluated in this work. Comparative information on acceptable FRM/FEM instrumentation performance characteristics for each pollutant as listed in 40 CFR Part 53 Table B-1 (see Appendix A) is provided as the last entry on each of the accompanying tables for the individual sensor tests.

It should be noted that in the figures for this and all other NO₂ sensors, the FEM employed to record the chamber conditions had a maximum reporting value of 200 ppb. Therefore, there were situations where the test sensors yielded a response well in excess of the FEM ceiling. This gives the appearance in the graphs that the sensors were reporting a significant positive bias at the upper challenge concentration which would not be correct. Only those values between 0 and 200 ppb were actually used in the development of statistics for this and all other NO₂ sensors. Actual sensor response is being shown here to reflect the ability of the sensor to actually respond to challenge conditions at or near 400 ppb.

5.1 Ozone Sensors

5.1.1 AGT Environmental Sensor

The AGT Environmental Sensor¹⁰ received for evaluation and as described by the collaborator, was designed for outdoor use by pedestrians and/or bicyclists and provides for enhanced environmental measurements in urban areas and in the vicinity of industrial areas¹¹. The sensor device can be used to monitor air quality by measuring traffic pollutants and industrial pollutants. This sensor is capable of measuring carbon monoxide (CO), carbon dioxide (CO₂), NO₂, O₃, particulate matter (PM₁₀), temperature, humidity, noise, atmospheric pressure and solar radiation (UV). Size and weight is comparable to other handheld devices (e.g. GPS devices) and it is powered by batteries and solar panels. Pollutants like ozone, carbon monoxide and nitrogen dioxide are detected using metal oxide semiconductor (MOS) sensors. Air quality is sensed with a MOS based component to detect a broad range of VOCs and correlates these measurements directly with CO₂ levels in the room. Other environmental parameters like temperature, humidity and atmospheric pressure are monitored using a combined temperature/humidity sensor and a barometer. In addition, an ambient light sensor can sense visible light, and the ultraviolet (UV) sensor is a broadband UVA-UVB-UVC sensor, sensitive to wavelengths from 220 to 370 nm. Noise levels, measured in decibels (dB), are detected using a microphone and electronics configured to measure sound using A-weighting. In order to achieve fast response of concentration measurement, outside air needs to be transported to all sensor components inside the housing. Therefore, fans are used to create this airflow through the device. The primary use of this airflow is to pull in ambient air and deliver it to the internal sensor components. The integrated 2000 mAh Lithium-Polymer (Li-Po) battery offers 4-8 hours of autonomous device operation – depending on measurement and sampling

¹⁰ Florian Zeiger, Marco F. Huber; Demonstration Abstract: Participatory Sensing enabled Environmental Monitoring in Smart Cities, 13th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN 2013), Berlin, Germany

¹¹ AGT's sensor was developed within AGT's Environmental Sensing project. Acknowledgements to Zacharias Boufidis, Marco Huber, Kostas Sasloglou, Georgios Mazarakis, Birte Ulrich, Ashok Kumar Chandra Sekaran, Roel Heremans, Andreas Merentitis, Nikolaos Frangiadakis, Martin Strohbach, Kerron Boothe, Christian Debes, Maria Niessen, James Rex, Environmental Sensing scrum team, Rutan GmbH, and the TECO research group

intervals. Solar cells are used for energy harvesting from the sun light contributing to the device's energy budget. It can be charged using a micro-USB cable. The device was also equipped with a sensor for particulate matter.

The AGT Environmental Sensor has two buttons for standard operations and all detailed configuration settings are performed via Smartphone app. The measurement range of the internal sensor components were designed so that the device can be used in different settings to enable citizens to monitor a variety of air quality conditions. The sensor device has no GPS receiver or display and is designed to be used with a Smartphone for data transmission, adding location/timestamp and sensor device configuration as part of its output. Communication between Smartphone and the AGT Environmental Sensor is done via Bluetooth. This system uses participatory sensing¹², and thus enables this powerful technology for larger scale environmental monitoring systems in the smart city context.¹³

The AGT Environmental Sensor was able to participate in all conducted tests. The sensor system showed relatively good response times and small lag times during the tests (~ 1 min). Also the ozone response was highly linear ($R^2 > 0.98$). It would appear that the sensor showed the greatest degree of response variability (37.7 ppb) under challenge conditions involving hot temperatures and high O₃ concentrations. Modest SO₂ positive interference was observed (7.5 ppb).

Testing was completed for the AGT Environmental Sensor under all conditions. Note that interference testing was performed only under normal conditions. Examples of the sensor's response under normal challenge conditions are shown for O₃ in Figure 2. The response of the AGT sensor is observed to be highly consistent with that of the reference monitor/trace over the full range of challenge concentrations.

Table 3. Summary of AGT Environmental Sensor Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)	O ₃ Int* (ppb)
						Low (ppb)	High (ppb)				
O ₃	Normal	0.9824	10.3	15.6	11.8	8.3	14.1	1	5	7.5	
	Hot	0.9933	13.6	12.4	18.1	6.8	37.7	1	6		
	Humid	0.9774	2.6	12.4	16.0	5.9	4.0	1	4		
	Cold	0.9772	7.2	9.8	11.3	2.6	6.1	1	3		
CFR O ₃	NA	NA	10	10	10 [^]	5	5	20	15	20	20

*Blank cells indicate that interference testing was not conducted under that condition. NA indicates no data were available to establish the response comparison.
[^] Value specific to the 2B Model 205 O₃ Analyzer

¹² Demonstration Abstract: Participatory Sensing enabled Environmental Monitoring in Smart Cities, Florian Zeiger, Marco F. Huber. Accepted for the 13th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN 2013), Berlin, Germany

¹³ F. Zeiger and Z. Boufidis, "Towards Future Internet services through crowdsourcing-based sensor platforms," International Journal of Communication Networks and Distributed Systems, vol. 11, no. 1, pp. 4–10, Jun. 2013.

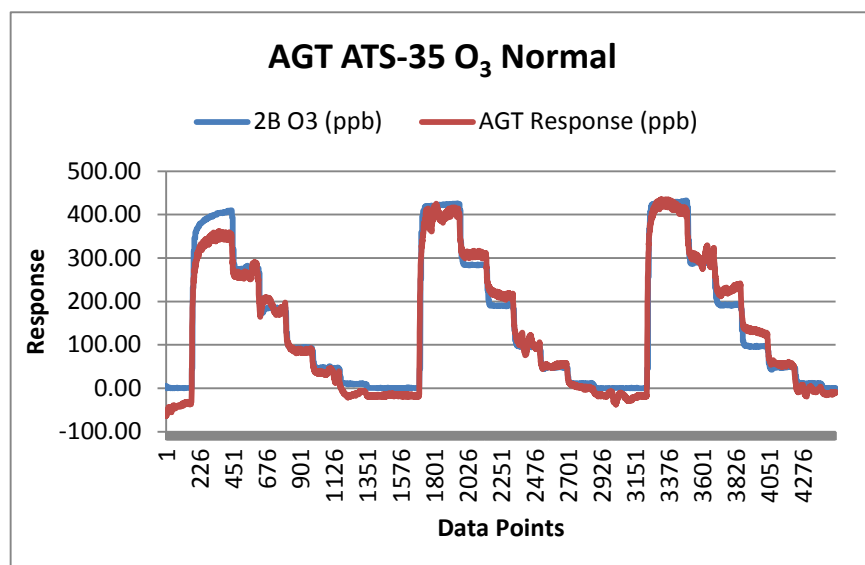


Figure 2. Example AGT ATS-35 Response for O₃ under Normal Challenge Conditions

5.1.2 CairClip

The CairClip was composed of an amperometric sensor, a micro fan that enables dynamic air sampling, a patented filter, and a highly-sensitive nanoamperes detection circuit. Data are stored in an integrated datalogger capable of retaining more than 28,000 points (1-min average). Sensor components were integrated into an aluminium-based casing cylinder (32 x 62 mm).

Testing was completed for the CairClip sensor under all conditions. The data are summarized in Table 4. Data could not be processed for the O₃ hot conditions because of a natural increase in response due to temperatures and the sensor type (amperometric). Note that interference testing was performed only under normal conditions. Examples of the sensor's response under normal challenge conditions are shown for O₃ in Figure 3.

Results obtained during this study were comparable to those observed in Cairpol internal test evaluations.¹⁴ Excellent linearity over the full operating range was observed ($R^2 > 0.99$). Limits of detection (≤ 11 ppb) were evident with excellent precision observed under both high and low challenge conditions (≤ 4 ppb).

Lag and rise time were higher than those observed in internal Cairpol testing where values typically < 3 mins have been obtained. These differences may be linked to the time it takes for the sensor to condition itself with O₃ under test chamber conditions employed here as compared to evaluations Cairpol has performed under ambient conditions.

As seen in Figure 3, the CairClip as tested showed highly similar trends with the reference monitor but always with a small obvious positive effect. The observed offset is due to the device's internal calibration coefficient (slope) that Cairpol uses to compensate for the lack

¹⁴ Zaouak, O., Aubert, B., Castang, J-B. Cost-efficient Miniature Sensors for Network Continuous Monitoring of Diffuse Pollution at the Low ppbv Level. Invited Presentation to the 2013 Air Sensors Workshop. Research Triangle Park, NC, March 20, 2013.

of sensitivity of the electrochemical sensor to NO₂ in comparison to its sensitivity to O₃ (being responsive to both O₃/NO₂).

Cairpol has also suggested that the positive effect might be the result of a lack of adequate conditioning time prior to start of the chamber trials. Exposure to zero grade air (as was the case here) requires the sensor to become “disconditioned” due to a lack of oxidizing species interacting with the sensor membrane. The need for proper conditioning is a noted feature of this sensor for best response.

To date, no disconditioning phenomenon have been observed under real conditions during actual monitoring events.¹⁵

Table 4. Summary of CairClip Sensor Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)
						Low (ppb)	High (ppb)			
O ₃	Normal	0.9958	4.6	10.8	4.3	1.7	3.4	1	4	0.37
	Hot	NA	NA	NA	NA	NA	NA	NA	NA	
	Humid	0.9989	2.8	8.6	4.6	1.7	2.4	0	8	
	Cold	0.9905	9.5	8.6	3.9	2.6	3.7	1	6	
CFR O ₃	NA	NA	10	10	10 [^]	5	5	20	15	20

*Blank cells indicate that interference testing was not conducted under that condition. NA indicates no data were available to establish the response comparison.

[^] Value specific to the 2B Model 205 O₃ Analyzer

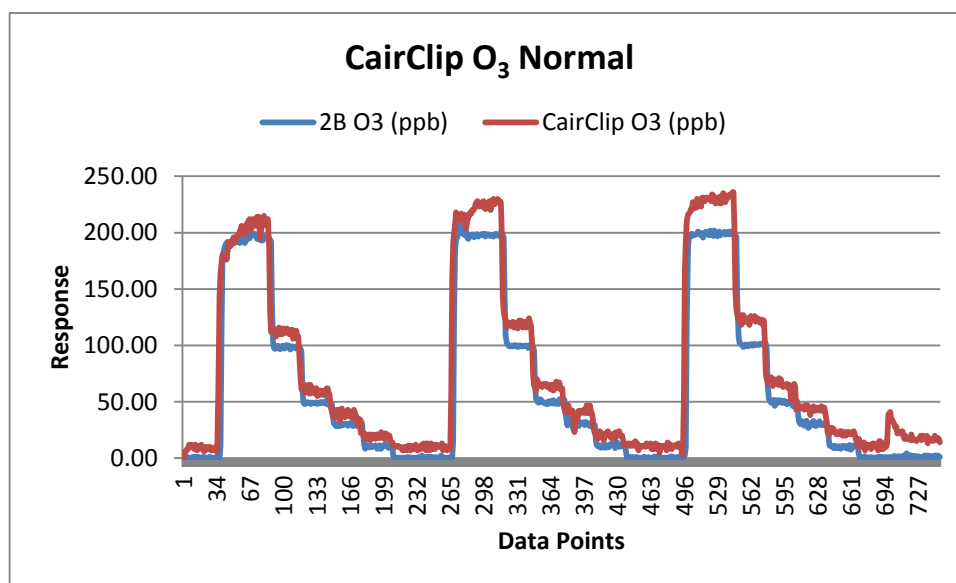


Figure 3. Example CairClip Response for O₃ under Normal Challenge Conditions

¹⁵ Zaouak, O., Aubert, B., Castang, J-B. Cost-efficient Miniature Sensors for Network Continuous Monitoring of Diffuse Pollution at the Low ppbv Level. Invited Presentation to the 2013 Air Sensors Workshop. Research Triangle Park, NC, March 20, 2013.

5.1.3 CitiSense

Preliminary testing of the CitiSense with 500 ppb O₃ yielded no response. As such, all further testing with O₃ was canceled. The believed failure of the device to respond to an initial challenge was that related to an aged electrochemical sensor (> 2 years of age). This is not an unexpected result as many MOS sensors have a limited lifespan regardless of their degree of use during such a time period. A full description of the CitiSense device and its properties are reported in section 6.2.4.

Table 5. Summary of CitiSense Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)	O ₃ Int* (ppb)
						Low (ppb)	High (ppb)				
O ₃	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
CFR O ₃	NA	NA	10	10	10 [^]	5	5	20	15	20	20

*Blank cells indicate that interference testing was not conducted under that condition. NA indicates no data were available to establish the response comparison.
[^]Value specific to the 2B Model 205 O₃ Analyzer

5.1.4 Dynamo

Testing was completed for the Dynamo sensor under all conditions. The data are summarized in Table 6. Note that interference testing was performed only under normal conditions. An example of the sensor's response for O₃ under normal challenge conditions is shown in Figure 4. The active range of the Dynamo sensor as reported by the developer is 10 ppb to 250 ppb. Any exposure to O₃ levels outside of this range would not be expected to be reported accurately. The Dynamo sensor was designed for use on mobile platforms (trucking fleets, etc.) that traverse areas expected to have O₃ concentrations well within this designated range.

The Dynamo sensor typically can respond to a range of resistance values as O₃ concentrations vary. The sensor was factory calibrated with exposure to 100 ppb of O₃, and the level of response set to equate to this concentration. The O₃ concentration was then reduced to 10 ppb, and the response adjusted to reflect this concentration response. These two factory adjustments give the correct scaling and slope over the main range of interest (10-100 ppb).

While the typical factory calibration is a two point challenge (10 and 100 ppb), a much larger range was applied in our testing (0 to 400 ppb). As observed in Table 6, acceptable linearity was observed over the full range (R² ≥ 0.95) but with significantly reduced response characteristics as a result of the factory calibration procedure. Even so, data revealed a multi-linearity curvature of the response and as stated above, this feature might have been related to the two point factory calibration pre-set into the device. Good precision (≤ 7 ppb) over all test conditions were observed. It should be noted that since the Dynamo is used in mobile data collection scenarios, short lag and rise times are paramount for good performance characteristics. As seen above, times ≤ 5 min were observed. We did note minor positive SO₂ (2.9 ppb) and sizeable NO₂ interference (15.6 ppb) under the test conditions.

Further slope linearity and sensor response improvements have taken place in factory since the time the Dynamo sensor unit was submitted for EPA testing.

Table 6. Summary of Dynamo Sensor Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)	NO ₂ Int* (ppb)
						Low (ppb)	High (ppb)				
O ₃	Normal	0.9466	7	11.5	4.1	0	11.7	1	2	2.9	15.6
	Hot	0.9885	4.3	11.7	5.4	3.6	5.3	1	5		
	Humid	0.9795	3.3	9.9	6.0	2.0	3.8	1	4		
	Cold	0.9820	6.1	10.9	4.4	0	5.5	1	5		
CFR O ₃	NA	NA	10	10	10 [^]	5	5	20	15	20	20

*Blank cells indicate that interference testing was not conducted under that condition. NA indicates no data were available to establish the response comparison.
[^] Value specific to the 2B Model 205 O₃ Analyzer

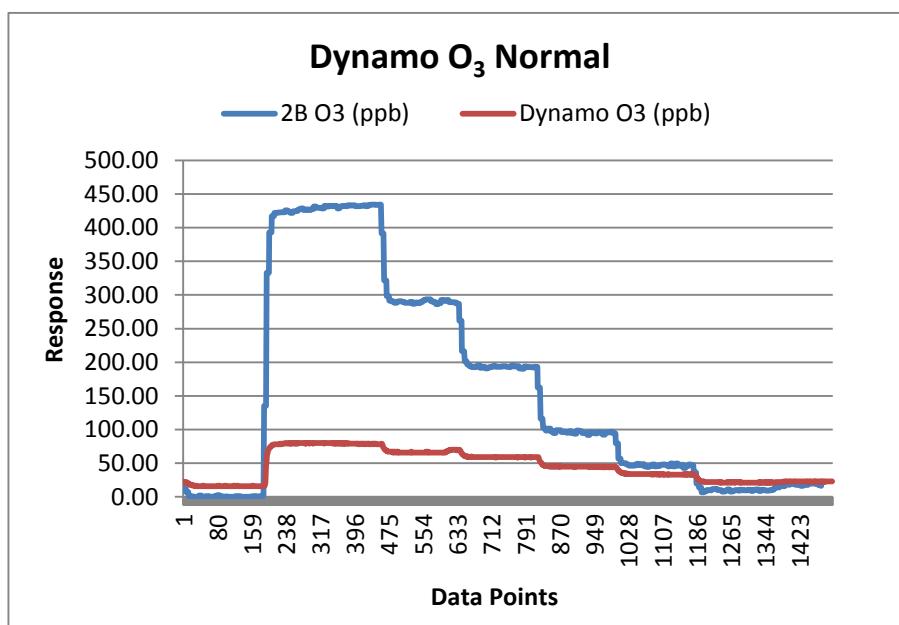


Figure 4. Example Dynamo Response for O₃ under Normal Challenge Conditions

5.1.5 U-Pod

Testing was performed for the U-Pod under normal and cold conditions. Data points were produced every 5 seconds and included battery voltage; temperature; humidity; light sensor output; and O₃ sensor output. Gas sensor data are reported as the output voltage of the e2v sensors. These values were then divided into a constant, 10,000, which was chosen arbitrarily to achieve a positive correlation with set-point concentrations.

The O₃ sensor used in the U-Pod is a commercially available MOS that retails for \$9 and is about the size of a large peanut (SGX Sensortech MiCS-2611). This sensor has previously been tested by the Hannigan group under a variety of ambient conditions, but never in a lab

setting at the tested concentrations and dynamics. The sensor is known to suffer from cross-sensitivity to other pollutants, to ambient conditions, and baseline drift. However, in 2-week co-location calibrations of multiple MiCS-2611 sensors with Colorado Department of Public Health and the Environment operated regulatory monitors; the sensors had median standard errors of 6.1 ppb¹⁶, on the order of the reported LDL here. Improved precision at lower temperature has been previously observed in testing, and this effect could likely be overcome by controlling sensor voltage. Converting sensor signal to concentration thus requires the use of multilinear regression, which increases calibration time and analysis complexity.

Findings in the current testing indicate that under normal and cold test conditions, a linear response ($R^2 > 0.88$) was obtainable. The precision error under normal challenge was somewhat high (46.2 ppb) but it did provide respectful LDL and IDL values (≤ 11.9). The device produced no measurable SO₂ interference.

The data are summarized in Table 7. Note that interference testing was performed only under normal conditions. Proper conditioning was not achieved in two of the tests (O₃ hot, O₃ humid) over the length of an entire test, and the variation between calibration sequences was such that the data could not be used for statistical analysis. In such cases, the sensor failed to provide an equilibrated starting output following installation into the chamber at the challenge condition. The primary source of these problems is hypothesized to be conditioning times of the sensor under chamber testing conditions.

The U-POD was received with an acrylic casing. Data we report here reflects testing performed with no casing surrounding the sensor board. Extensive laboratory trials were conducted that initially provided reduced sensor response or distorted response (data not shown). It is hypothesized that the acrylic case to the U-Pod was absorbing ozone at a rate sufficient to depress the levels present in the test chamber and that this rate requires time on the order of hours to reach a state of equilibrium. We subsequently removed the case and tested the sensor successfully over the full challenge range.

Table 7. Summary of U-Pod Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)	O ₃ Int* (ppb)
						Low (ppb)	High (ppb)				
O ₃	Normal	0.8775	46.2	3.4	11.9	0.3	1.6	3	8	0	NA
	Hot	NA	NA	NA	NA	NA	NA	NA	NA		
	Humid	NA	NA	NA	NA	NA	NA	NA	NA		
	Cold	0.9546	6.5	7.8	0.9	0.1	3.6	1	5		
CFR O ₃	NA	NA	10	10	10 [^]	5	5	20	15	20	20

*Blank cells indicate that interference testing was not conducted under that condition . NA indicates no data were available to establish the response comparison.
[^] Value specific to the 2B Model 205 O₃ Analyzer

¹⁶ Piedrahita, R., Xiang, Y., Masson, N., Ortega, J., Collier, A., Jiang, Y., Li, K., Dick, R., Lv, Q., Hannigan, M., Shang, L. The next generation of low-cost personal air quality sensors for quantitative exposure monitoring. Atmospheric Measurement Techniques Discussion. 7; 2425-2457, 2014. Doi:10.5194/amtd-7-2425-2014.

5.2 Nitrogen Dioxide Sensors

5.2.1 AGT Environmental Sensor

Detailed information about the AGT Environmental Sensor is provided previously in Section 6.1.1. Primary testing was completed for the AGT environmental sensor under all conditions. The data are summarized below in Table 8. Note that interference testing was performed only under normal conditions. Examples of the sensor's response under normal challenge conditions are shown for NO₂ in Figure 5. It should be noted that in the figures for this and all other NO₂ sensors, the FEM employed to record the chamber conditions had a maximum reporting value of 200 ppb. Therefore, there were situations where the test sensors yielded a response well in excess of the FEM ceiling. This gives the appearance in the graphs that the sensors were reporting a significant positive bias at the upper challenge concentration which would not be correct. Only those values between 0 and 200 ppb were actually used in the development of statistics for this and all other NO₂ sensors. Actual sensor response is being shown here to reflect the ability of the sensor to actually respond to challenge conditions at or near 400 ppb.

The device provided excellent linearity over the test range ($R^2 \geq 0.99$) with a very high degree of precision (≤ 7.5 ppb). Detection limits were on the order of 10-20 ppb. It should be noted that while the device reported concentrations in good agreement with reference monitors in the 0 to 200 ppb (Figure 5), an artificial and distinct positive bias was evident under high challenge conditions followed by a sharp drop to more appropriate concentration estimates. There can be several reasons for this behavior. Taking into account the sensor characteristics (Figure 6), disturbances in the 100-200 ppb concentration range can have significant effects on the output of the sensor. One candidate for such a disturbance can be for example the recharging of the battery which leads to non-constant temperature situations inside the sensor case – and thus, can directly influence the raw sensor output. Nevertheless, this behavior is subject to future research as we believe it can be resolved.

The device had fast lag times (~ 2 /min) but rise times increased under hot challenge conditions (20 min). A distinct positive SO₂ bias was observed (19.5 ppb).

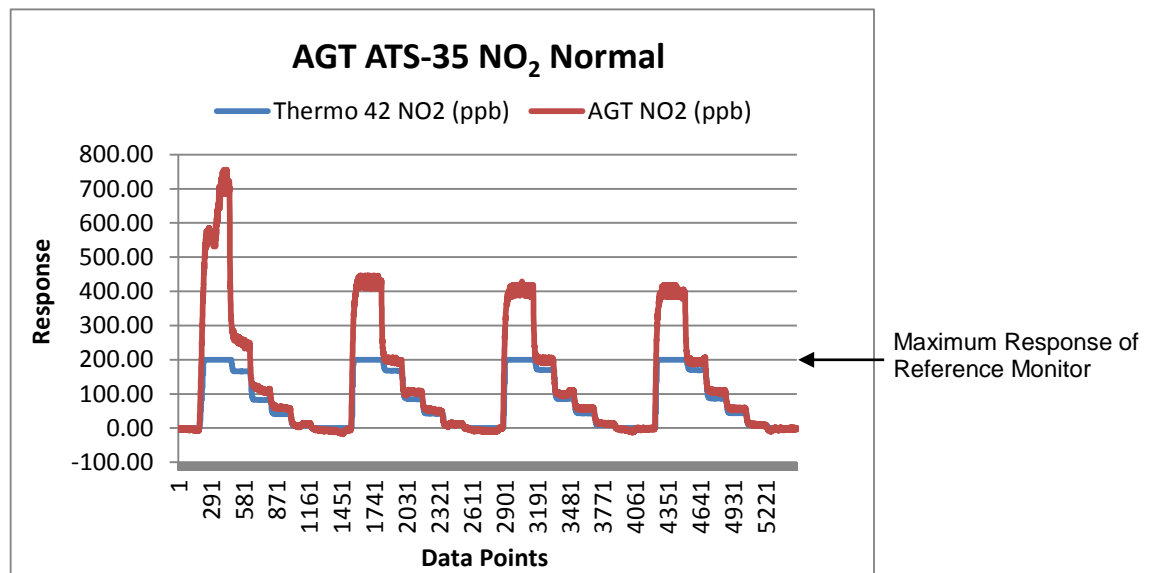


Figure 5. Example AGT ATS-35 Response for NO₂ under Normal Challenge Conditions

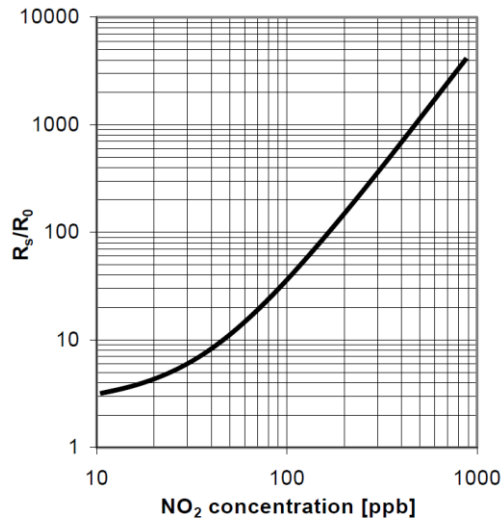


Figure 6. Sensor Characteristics for AGT NO₂ Sensor

Table 8. Summary of AGT Environmental Sensor Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)	NO ₂ Int* (ppb)
						Low (ppb)	High (ppb)				
NO ₂	Normal	0.9972	1.2	15.0	9.5	1.8	2.3	1	5	19.5	NA
	Hot	0.9919	6.4	13.6	24.0	5.7	8.1	1	20		
	Humid	0.9937	7.4	17.7	22.8	2.7	5.2	1	7		
	Cold	0.9917	7.5	10.2	5.2	0.8	6.8	1	6		
CFR NO ₂	NA	NA	10	10	10 [^]	5	5	20	15	20	20

*Blank cells indicate that interference testing was not conducted under that condition. NA indicates no data were available to establish the response comparison.
[^] Value specific to the Thermo Model 42C NO/NO₂/NO_x Analyzer

5.2.2 AirCasting

We experienced numerous lost data collection episodes in our testing of the AirCasting monitor. Eventually, resources limited us to findings associated with NO₂ normal testing conditions. We also experienced several spontaneous software crashes that impacted the availability of data used in this analysis. In addition, we sometimes had difficulty establishing and maintaining the Bluetooth connection between the AirCasting monitor and the Android device. This might have been due to the signal being blocked by the walls of the test chamber and the supporting testing hardware and not a feature of the device itself under normal ambient operating conditions.

Chamber tests performed by the developer have been previously reported.¹⁷ The collaborator had determined that the MiCS-271 metal-oxide sensor provided reasonable NO₂ response curves. It was noted that the response curves were not as sharp as those produced by the tests reported here in the EPA laboratories. This might well have been due to the small chamber system they used and which might have had inadequate mixing of the challenge gas. The sensitivity response performed directly by the AirCasting collaborator appeared to be slightly higher as compared to those in our EPA-performed tests. The in-house AirCaster tests did however, note a word of caution. It was apparent that high out of the box variability existed between NO₂ sensors from the manufacturer and therefore there is a need to individually calibrate each sensor. In-house AirCasting tests also indicated the sensitivity of the MiCS-2710 NO₂ diminished as the NO₂ concentration climbed above 100 ppb. Supporting material for the sensor can be found in the reference section.^{18,19,20}

The data are summarized below in Table 9. An example of the sensor's response to NO₂ under normal challenge conditions is shown in Figure 7.

As can be seen, the device provided good linearity ($R^2 > 0.98$) over the full test range with excellent precision (3 ppb). It yielded extremely fast rise and lag times (≤ 1 min). As depicted in Figure 7, the device showed excellent reproduction of the reference monitor response until challenge concentrations exceeded 100 ppb.

Table 9. Summary of AirCasting Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)
						Low (ppb)	High (ppb)		
NO ₂	Normal	0.9846	3.0	11.6	14.6	1.1	1.0	0	4
CFR NO ₂	NA	NA	10	10	10 [^]	5	5	20	15

NA indicates no data were available to establish the response comparison.
[^] Value specific to the Thermo Model 42C NO/NO₂/NO_x Analyzer

¹⁷ AirCasting test results and analysis:
<http://www.takingspace.org/evaluating-low-cost-gas-sensors/>.

¹⁸ AirCasting instruction manual:
http://www.habitatmap.org/habitatmap_docs/HowToBuildAnAirCastingAirMonitor.pdf

¹⁹ AirCasting website: <http://aircasting.org/>

²⁰ AirCasting app download: <https://play.google.com/store/apps/details?id=pl.llp.aircasting&hl=en>

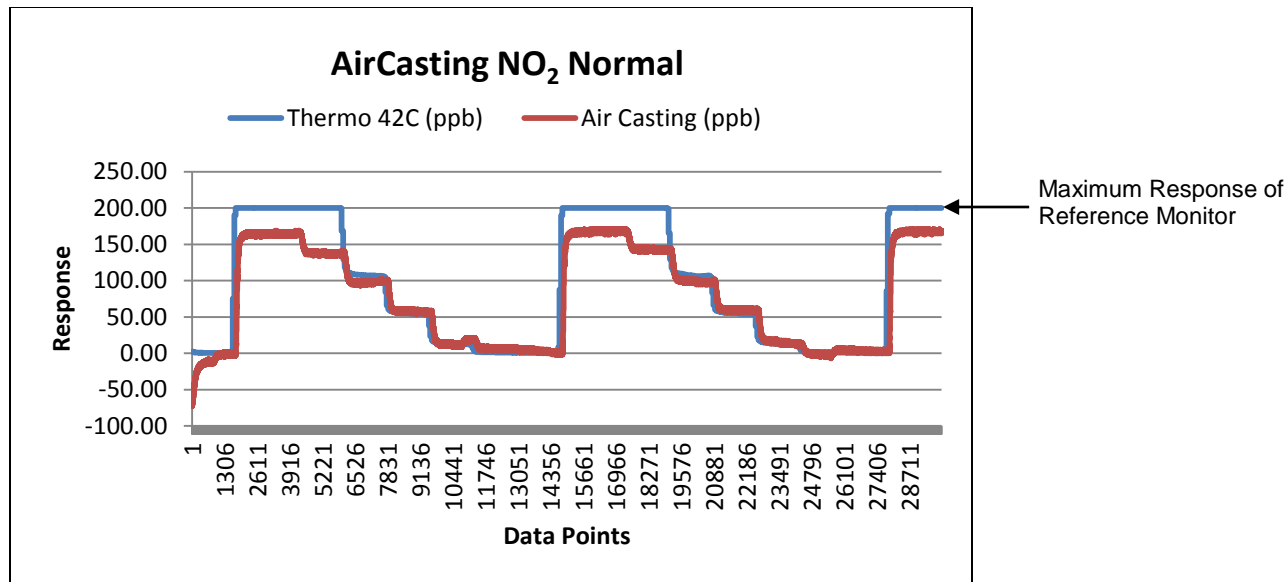


Figure 7. Example AirCasting Response for NO₂ under Normal Challenge Conditions

5.2.3 CairClip

Primary testing was completed for the CairClip sensor under all conditions. The data are summarized in Table 10. Note that interference testing was performed only under normal conditions. Examples of the sensor's response under normal challenge conditions are shown for NO₂ in Figure 8.

As for the O₃ tests reported here, similar results as those obtained during in-house Cairpol chambers tests were obtained. Excellent linearity was observed ($R^2 \geq 0.99$) with good precision (≤ 9.3 ppb). It must be recognized that this O₃/NO₂ sensor tested here is by nature, less sensitive to NO₂ as compared to O₃. That also explains why the value concerning O₃ exposure was slightly higher than expected at the high test conditions (concentrations >150 ppb). The value of the calibration coefficient applied to the device's response has been knowingly increased by Cairpol to compensate for this difference in sensitivity between the two gases. We observed minimal SO₂ interference (0.58 ppb) with this sensor.

Lag and rise time values on the order of 0-8 minutes, are higher than those generally observed in internal Cairpol chamber testing. As can be seen in Figure 8, there was a constant shift regarding the lag time and the rise time between the sensor and the reference monitor output. A disfunction in the Cairsoft (software used for data downloading) has since been detected as a result of the data provided here and is believed to have been responsible for this shift. Cairpol indicates it has subsequently corrected this software function.

Table 10. Summary of CairClip Sensor Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)
						Low (ppb)	High (ppb)			
NO ₂	Normal	0.9968	3.8	7.0	5.2	3.6	2.0	2	5	0.58
	Hot	0.9978	2.9	0	1.4	0.6	5.4	4	8	
	Humid	0.9975	4.2	8.6	4.8	2.4	2.3	4	3	
	Cold	0.9896	9.3	8.3	5.9	2.3	3.2	0	5	
CFR NO ₂	NA	NA	10	10	10 [^]	5	5	20	15	20

*Blank cells indicate that interference testing was not conducted under that condition. NA indicates no data were available to establish the response comparison.
[^] Value specific to the Thermo Model 42C NO/NO₂/NO_x Analyzer

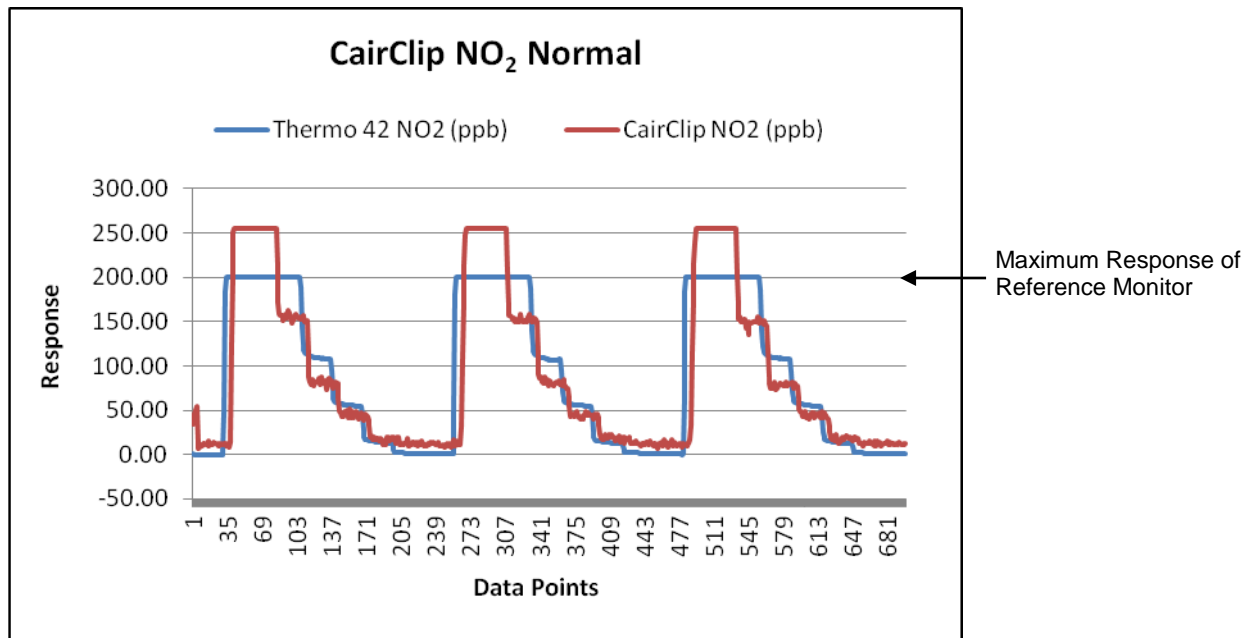


Figure 8. Example CairClip Response for NO₂ under Normal Challenge Conditions

5.2.4 CitiSense

The CitiSense air quality monitoring device was designed to be highly-portable and operate for relatively long periods of time between battery charges. The device, which communicates measurements to a paired Smartphone device over Bluetooth, can go approximately five days between charges. The device measures temperature, humidity, barometric air pressure, O₃, CO, and NO₂. Measurements are taken every six seconds and transmitted immediately over the Bluetooth channel to any paired devices. The device contains no long-term storage and no display; all storage, processing, and visualization is done in the

CitiSense application for Android phones. Further details about the design of the sensor node and its uses can be found in the reference section.²¹

The sensor device and its protective enclosure are custom designs by the CitiSense research team at the University of California, San Diego. The actual sensing elements used in the device are off-the-shelf components provided by several manufacturers. The electrochemical ozone sensor used in the device is the O3-3E-1 4-series adaption Sensoric Ozone sensor from CityTechnology.²² The electrochemical carbon monoxide sensor, CO-AX, and the electrochemical nitrogen dioxide sensor, NO2-A1, are both from Alphasense.^{23,24} Each sensor on the device was calibrated when initially set up. It is recognized that the sensors must be re-calibrated once every three to six months and replaced once every twelve to sixteen months to ensure accurate results. Low-level details about the design of the sensor board and its conditioning circuit can be found in the reference section.²⁵

Primary testing was performed for the CitiSense with NO₂ under all conditions. The data are summarized below in Table 11. Note that interference testing was performed only under normal conditions. Two of the tests (NO₂ cold and NO₂ hot) failed to produce viable data for statistical analysis. An example of the sensor's response for NO₂ under normal challenge conditions is shown in Figure 9.

The device yielded good linearity over the test range ($R^2 > 0.97$). Precision was notably poorer under humid test challenge (23.3 ppb). Reasonable deviation in response was observed at high and low NO₂ challenges (≤ 10 ppb) but humid conditions impacted IDL performance (68.5 ppb). While lag times were of no consequence (< 1 min), a rise time of 18 minutes was reported under normal test conditions. The device had an appreciable bias to SO₂ challenge (34.2 ppb).

Table 11. Summary of CitiSense Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)	NO ₂ Int* (ppb)
						Low (ppb)	High (ppb)				
NO ₂	Normal	0.9772	4.6	7.7	13.4	3.7	8.7	0	18	34.2	NA
	Hot	NA	NA	NA	NA	NA	NA	NA	NA		
	Humid	0.9722	23.3	19.6	68.5	8.4	10.0	0	8		
	Cold	NA	NA	NA	NA	NA	NA	NA	NA		
CFR NO ₂	NA	NA	10	10	10 [^]	5	5	20	15	20	20

*Blank cells indicate that interference testing was not conducted under that condition. NA indicates no data were available to establish the response comparison.
[^] Value specific to the Thermo Model 42C NO/NO₂/NO_x Analyzer

²¹ Zappi, P., Bales, E., Park, J. H., Griswold, W., & Rosing, T. Š. (2012, April). The citisense air quality monitoring mobile sensor node. In Proceedings of the 11th ACM/IEEE Conference on Information Processing in Sensor Networks, Beijing, China.

²² Sensoric O3-31-1 Ozone Sensor spec sheet, CityTechnology. <http://www.citytech.com/PDF-Datasheets/o33e1.pdf>

²³ CO-AX Carbon Monoxide Sensor spec sheet, Alphasense. <http://www.alphasense.com/WEB1213/wp-content/uploads/2013/10/COAX.pdf>

²⁴ NO2-A1 Nitrogen Dioxide Sensor spec sheet, Alphasense. <http://www.alphasense.com/WEB1213/wp-content/uploads/2013/07/NO2A1.pdf>

²⁵ Zappi, P. The CitiSense Air Quality Sensor Board manual. Tech Report (in Press)

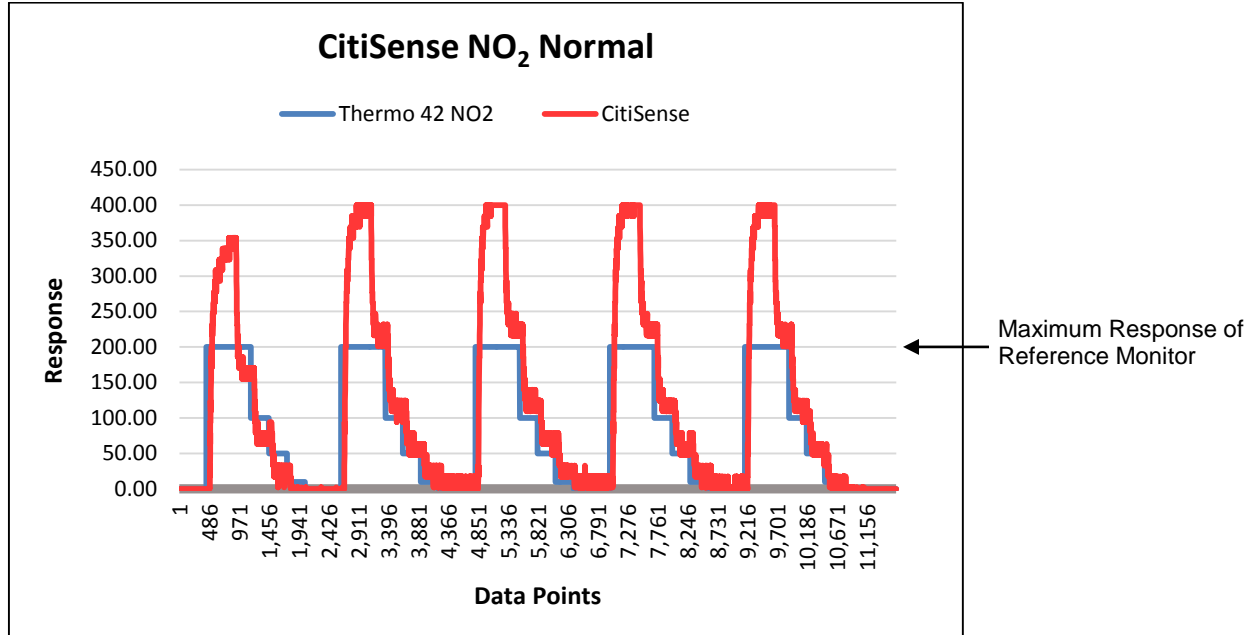


Figure 9. Example CitiSense Response for NO₂ under Normal Challenge Conditions

5.2.5 Platypus

The Platypus Technologies prototype NO₂ monitor uses a liquid crystal (LC) sensor to detect the target gas. Under controlled conditions, a thin film of LC rotates the polarization of light waves that pass through it. This rotation can be monitored visually or with photodiodes by placing the LC film between crossed polarizing filters. This light rotating property is used in liquid crystal displays for TVs and computers: each pixel is a tiny volume of liquid crystal, and changes in electric fields control the orientation of the LC molecules, which in turn determines amount of light passing through each pixel, thereby creating the picture on the screen. Platypus has adapted this concept by inducing the change in orientation of LC molecules on a film, supported on chemically functionalized surface, upon exposure to target gas.²⁶

The sensor in the prototype NO₂ monitor is a thin circular film of LC 5 mm in diameter, mounted on a metal strip that slides into the monitor without the need for tools (Appendix B). Device electronics monitor the light intensity transmitted through the LC film. The sensor is configured so that LC molecules orient parallel with the sensor surface when there is no NO₂ present, which allows light to pass through the LC layer when viewed through crossed polarizers. Exposure to NO₂ causes the LC molecules to re-orient perpendicular to the surface, blocking the transmission of light through the sensor. When NO₂ concentration is once more below the level of detection, the LC molecules return to the original parallel alignment. Changes in light intensity are converted to voltages that are used to calculate target concentration for display using an algorithm. The prototype monitor is capable of detecting ppb levels of NO₂

²⁶ Reviewed in Shah, R.; Abbott, N.L., "Principles for Measurement of Chemical Exposure based on Recognition-Driven Anchoring Transitions in Liquid Crystals, Science, 293, 1296-1299, 2001

when exposed for a few minutes. Further development is under way at Platypus to improve response times, sensitivity and linearity for specific detection of a range of gas targets.

In the primary testing performed here, only normal NO₂ conditions could be easily accommodated. Because the device was not amenable for direct chamber testing, chamber challenge gas was supplied to the unit using a gas transfer kit provided by Platypus. Following each challenge (change in chamber concentration), the LC film in the sensor was replaced and the next measurement initiated. The monitor was tested for replicate exposures to 100, 150, 200, 300 and 400 ppb NO₂. Note that interference testing was performed only under normal conditions.

The device provided reasonable linearity over the test range ($R^2 \geq 0.79$) with a precision of 18 ppb. Because the device is not capable of collecting a continuous data output (one data value per LC film) we were unable to report findings on many performance characteristics. Extremely high O₃ bias was observed (405 ppb) which was not a characteristic Platypus had observed in their own internal testing in developing the prototype tested here.

Table 12. Summary of Platypus Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int (ppb)	O ₃ Int (ppb)
						Low (ppb)	High (ppb)				
NO ₂	Normal	0.7956	18.0	NA	NA	NA	NA	NA	NA	0	405
CFR NO ₂	NA	NA	10	10	10 [^]	5	5	20	15	20	20

NA indicates no data were available to establish the response comparison.
[^] Value specific to the Thermo Model 42C NO/NO₂/NO_x Analyzer

5.2.6 U-Pod

Testing was performed for the U-Pod under all conditions. The data are summarized below in Table 13. Note that interference testing was performed only under normal conditions. Proper conditioning as evident in a stable response output at the outset of the test run, was not achieved in two of the tests (NO₂ normal, and NO₂ cold) therefore data obtained during these challenges could not be used for statistical analysis.

Similar to the O₃ sensor used in the U-Pod, the NO₂ sensor is a MOS that retails for \$7 (SGX Sensortech MiCS-2710). In these lab tests the sensor displayed good performance, similar to what has been observed in ambient co-location calibrations.²⁷ The high linearity from regression ($R^2 \geq 0.98$) is expected at such high concentrations, but this is often not the case at lower concentrations, where there is some log-like curvature that must be modeled. As with the O₃ sensor, this sensor performs well in colder temperatures, but this was not demonstrated in the lab testing due to the aforementioned instability at the initiation stage (equilibration). The slow rise times listed in these results are not apparent in co-location field calibrations, where lag times do not appear to be an issue when using minute averaged data. Again, this may be

²⁷ Piedrahita, R., Xiang, Y., Masson, N., Ortega, J., Collier, A., Jiang, Y., Li, K., Dick, R., Lv, Q., Hannigan, M., Shang, L. The next generation of low-cost personal air quality sensors for quantitative exposure monitoring. Atmospheric Measurement Techniques Discussion. 7; 2425-2457, 2014. Doi:10.5194/amtd-7-2425-2014.

because concentrations seen in the field co-locations are usually much lower than the range tested here. We observed no measurable SO₂ interference under the challenge testing.

Table 13. Summary of U-Pod Testing

Analyte	Conditions	Linearity (R ²)	Precision (ppb)	LDL (ppb)	IDL (ppb)	Resolution		Lag Time (min)	Rise Time (min)	SO ₂ Int* (ppb)	NO ₂ Int* (ppb)
						Low (ppb)	High (ppb)				
NO ₂	Normal	NA	NA	NA	NA	NA	NA	NA	NA	0	
	Hot	0.9851	5.0	4.2	11.7	1.3	4.1	1	33		
	Humid	0.9815	2.6	6.9	2.5	0.1	1.7	1	21		
	Cold	NA	NA	NA	NA	NA	NA	NA	NA		
CFR NO ₂	NA	NA	10	10	10 [^]	5	5	20	15	20	20

*Blank cells indicate that interference testing was not conducted under that condition. NA indicates no data were available to establish the response comparison.
[^] Value specific to the Thermo Model 42C NO/NO₂/NO_x Analyzer

6. Study Limitations

It must be recognized that the scope of this low cost sensor performance evaluation was limited with respect to a number of primary parameters:

- The resources of the U.S. EPA to conduct the extensive laboratory tests defined herein, and
- The scope of the performance testing that could be performed while being extensive was not meant to define full FRM or FEM qualifying conditions.

6.1 Resource Limitations

6.1.1 Minimal Findings on Intra-sensor Performance Characteristics

Resource limitations typically only allowed for a single sensor provided by the collaborating institution to be examined. Therefore, this report has minimal findings on intra-sensor performance characteristics. Such variability may be highly important as it was noted during the testing that upon occasion, more than one provided sensor failed to respond during initial rounds of testing and had to be replaced by the manufacturer. It is not known if the failures in such events were in response to a poor sensing element (the basic pollutant measurement interface), or some failure of the assembled sensor system. The U.S. EPA attempted no diagnostics of such events and merely communicated with collaborators that a failure had occurred and an alternative device (replacement) was needed if testing was to be performed.

6.1.2 Minimal Environmental and Interfering Agent Testing Conditions

Resources also prevented the U.S. EPA from examining the sensors under a wide variety of environmental and interfering agent conditions. Single “cold” and “hot” temperature conditions as defined in the Study Approach were employed as well as a single, relatively high (>200 ppb) challenge concentrations of either O₃, NO₂ or SO₂ were performed. None of the tests were conducted with co-varying environmental and co-pollutant test atmospheres. Likewise, one would have liked to examine the response of these sensors to varying RH and temperature with respect to pollutant concentration changes. Such examinations would have had a significant impact on the total amount of laboratory trials that could be afforded in this instance and as such were not performed.

6.1.3 Limited Number of Sensors

This work represented a limited survey of all low cost sensors available to interested end users. Based on the U.S. EPA’s own market survey prior to initiating the world-wide call for applicants, those who eventually applied represented a large portion of the applicable sensors meeting the study inclusion criteria but not all openly available in the market place. No stigma should be attached to sensors/sensor manufacturers not appearing in this report. The parties agreeing to share their devices and ultimately reporting their data findings with the general public here are to be applauded for their openness and willingness to helping to advance low cost sensor technology.

Table 14: Sensor Specifications

Manufacturer	Model #	Sensor type	Pollutant monitoring capability	Data storage/transmission	Battery type	Battery life (hrs)	Data output	Size (l/w/h) (cm)	Weight (g)	Notes
AGT	AGT Environmental Sensor	MOS	O ₃ , NO _x , CO, VOC, particulate matter	Bluetooth to Smartphone or Bluetooth/USB connection to PC	Li-Ion	4-8 hrs (depending on sampling interval)	Concentration if calibrated, raw data if not calibrated	13 x 5.8 x 2.5	170 g	Sensor can be configured via PC or smartphone
HabitatMap, Manhattan College, New York City College of Technology	AirCasting Air Monitor	MOS	NO ₂	Data storage: Android phone or tablet, AirCasting server Transmission: Bluetooth, Cellular network, Wi-Fi	Li-ion	4 hrs	Voltage or Analog Value	7.62 x 6.35 x 7.62	225g	
Cairpol	Cairclip	3 electrodes Electrochemical cell	Combined O ₃ /NO ₂	Internal storage up to 20 days (1 min-mean). USB data transmission using the specific software Cairsoft	Li-Po	From 48 h (continuous monitoring) to several weeks (stand by mode)	Concentration (ppbv)	diameter: 3.2 length: 6.2	55g	Display: LCD screen, Real time. Dynamic sampling using microfan Range (ppbv) 0-250
CitiSense	CARTOLA	Electrochemical	CO, NO ₂ , O ₃	Streams data wirelessly to paired mobile phone that runs the CitiSense application. No on-device storage, only stored once on phone.	Li-ion	Approx. 120 hours	Concentration (ppm)	10.8 x 6.7 x 3.8	Approx. 200 g	
Weather Telematics	WT-SU1 Dynamo	MOS	O ₃	Data collected and incorporated in main weather data string, transmitted over	N/A	N/A	Concentration (ppb)	Part of main weather sensor	160g (excluding cable)	

				CANBUS connection to data hub then RS232 to GSM modem or PC software				18 x 5.5 x 5		
Platypus Technologies LLC	Prototype	Liquid crystal	NO ₂	Display, RS-232	Ni Zn	2 hours w/ pump running @ full speed	Display (ppm) or voltage	15.5 x 8.3 x 4.3	508g	
CU Boulder Hannigan Lab	U-Pod	MOS, electrochemical, PID, NDIR	MOS: O ₃ , NO ₂ , CO, VOCs. NDIR: CO ₂ . PID: VOCs. Electrochemical: CO, NO, NO ₂ , O ₃ , SO ₂	MicroSD storage. Can also be configured with WiFi, Bluetooth	Can be configured for use with Li-ion and lead-acid batteries	12-100 hours, varies with battery selection	Voltage	22 x 19 x 10	1000-2000g	

7. Conclusions

A number of definitive conclusions are evident from this laboratory-based examination of low cost sensor performance. First, it is apparent that direct challenge via a well characterized exposure chamber was not only possible but proved to be a reasonable means of establishing basic performance characteristics of the devices. With rare exception was there evidence of gas phase interaction (reactivity) between sensor devices and the challenge atmosphere that might have influenced test results. This indicates that the test chamber and its supporting components (gas delivery system, environmental controls (RH, temperature), in-line test atmosphere system) were of sufficient materials and protocols to ensure valid test results. Careful characterization of the chamber prior to initiation of the testing (e.g., reference monitor response versus change in test atmosphere, stability of test atmosphere under static conditions, impact of changing environmental conditions upon reference monitors) ensured defensible evaluation of the devices under a wide range of testing scenarios. This being said, it would have been profitable for the test chamber to have had the capability of providing environmental conditions more varied with respect to both temperature and relative humidity. Resources limitations prevented design of more advanced environmental controls into the test chamber.

While most of the sensors evaluated had little or no obvious unwanted interaction with the test atmosphere itself, it should be recognized that in some instances (O_3), some interaction (reactivity) between the test atmosphere and the casing surrounding a sensor was established or hypothesized. In such cases, removal of the plastic casing often significantly improved performance. We also had to remove casings from some of the sensors to accommodate their overall size to fit within the chamber and therefore potential reactivity was not able to be directly tested for every sensor evaluated. Even though the testing chamber was designed to deliver a high output of test gas atmosphere (flow through rate of 10 l/min) to combat any potential for sensor starvation, sensor proximity to reactive surfaces is an issue of potential performance consequence that should be considered in their design. Higher or lower chamber flow rates could have changed performance for any of the sensors. Since no testing was conducted under true ambient conditions, it is not known if such an “excess” of gas interaction with a sensor might have been sufficient to overcome any potential for starvation/equilibration with respect to casing materials. Without question, it would be wise for sensor developers to encase sensors with materials fully characterized for their potential for gas phase reactivity. Even proximity of the sensor interface (position above the surface of the casing) might need to be considered to ensure the adequacy of the sensor design. In addition, recommended stabilization time prior to data collection would be highly desirable to ensure adequate performance of the sensor.

The sensors evaluated here often exhibited a high degree of linearity (typically $R^2 > 0.9$) over an extremely large test range. For both O_3 and NO_2 , the upper end of the challenge conditions (> 200 ppb) would represent very unique ambient events that such sensors might never encounter in non-occupational environments. Likewise, most of the sensors would appear to offer detection sensitivities in the low ppb range and with precision (repeatability) well within typically acceptable values. Such findings are encouraging for their potential applicability for citizen science and even professionally-performed research endeavors. Of significance here is the often short rise and lag times observed with the sensors (e.g., ~ 1 min). The sharp stair-step pattern of response in the graphical displays of performance under test conditions is a clear indication of how quickly most of the sensor responded. We saw little evidence of hysteresis or failure of the sensors by retaining “memory” of the previous challenge condition after test atmospheres had changed to a new concentration. This would indicate that these low cost sensors might have potential applicability for use in non-static situations (movement with respect to spatial setting). Even so, the tests performed here were not of sufficient design to

evaluate very short spatial or even temporal impacts that one might experience if for instance the sensor was being used to investigate on-road pollutant concentrations.

Few if any of the sensors evaluated had built-in zero or response calibration features. Such features on higher priced (often occupational) sensors would be advantageous for technically trained end users. That being said, we only rarely observed some positive bias (concentration response > 0 ppb) at the start of any testing sequence when pollutant-free air was being supplied to the test chamber. This result linked to the often good linearity of response is a possible indication that for the sensors tested, commonly used zero and span procedures might be replaced with simple collocation (normalization) comparisons with reference monitors in the users environmental setting. That being said, we sometimes observed sensors provided for evaluation yield no initial usable test data and having to be replaced by replicate units for the evaluations to proceed. This is an important finding and users deploying low cost sensors need to ensure that their device has been either calibrated in the more traditional manner or compared with ambient monitoring data from collocation trials before being used in data collections. The reason for the aforementioned failures may be linked to possible lot-to-lot and even intra-lot variability of the primary sensing element often being incorporated into many of the low cost sensors. In other words, quality assurance procedures associated with the primary manufactured sensing elements would appear to be one of consequence.

This evaluation did not have the capability of examining long-term performance response characteristics (e.g., drift of signal over extended time periods of constant challenge, stability of response with respect to sensor lifetime). Even so, some sensors originally provided for testing and being more than two years of age failed to respond, indicating some potential lifespan issues. While we cannot define the useable lifespan for any of the sensors evaluated, a good rule of thumb might be something on the order of 1-2 years, especially for MOS and similar sensing elements. End users should perform at least one of the evaluation procedures described above on a reoccurring basis to ensure the operation status of their device. It is not known at this time if such sensors yield a gradual decay in response or sharp decline at the end of their lifespan.

The evaluations performed here represent a first step in understanding how the low cost sensor segment compares to recognized FRM/FEM specifications. The results were not only encouraging but in many instances quite surprising with respect to how well the devices performed for certain performance characteristics (e.g., detection limits, linearity, precision, rise and lag times). It should be noted that ultimately resource limitations sometimes prevented evaluation of every sensor under all of the test conditions.

Lastly, it should be recognized that the named sensor developers submitting their devices for evaluations here are to be applauded for their willingness to share their technology (and test results) with others, including the general public. It is apparent in our discussions with not only these sensor developers, but the market segment as a whole, that there is a real desire to provide sensors meeting a wide range of air quality monitoring needs. Additional testing, including evaluation of sensors of this nature under true ambient conditions, would provide for enhanced understanding of how well these sensors respond to changing environmental conditions and their applicability for various data collection scenarios.

Appendix A

Technical Aspects- FRM/FEM Performance Parameters

40 CFR Part 53 Table B-1: Performance Specifications for Automated Methods

Performance parameter	Units ¹	SO ₂		O ₃ (Std. range)	NO ₂ (Std. range)
		Std. range ³	Lower range ^{2,3}		
1. Range	ppm	0-0.5	<0.5	0-0.5	0-0.5
2. Noise	ppm	0.001	0.0005	0.005	0.005
3. Lower detectable limit	ppm	0.002	0.001	0.010	0.010
4. Interference equivalent					
Each interferent	ppm	±0.005	⁴ ±0.005	±0.02	±0.02
Total, all interferents	ppm	---	---	0.06	0.04
5. Zero drift, 12 and 24 hour	ppm	±0.004	±0.002	±0.02	±0.02
6. Span drift, 24 hour					
20% of upper range limit	Percent	---	---	±20.0	±20.0
80% of upper range limit	Percent	±3.0	±3.0	±5.0	±5.0
7. Lag time	Minutes	2	2	20	20
8. Rise time	Minutes	2	2	15	15
9. Fall time	Minutes	2	2	15	15
10. Precision					
20 % of upper range limit	ppm	---	---	0.010	0.020
	Percent	2	2	---	---
80 % of upper range limit	ppm	---	---	0.010	0.030
	Percent	2	2	---	---

Appendix B

Photographs of Sensors

1. AGT Environmental Sensor



2. AirCasting App and AirCasting Air Monitor



AirCasting App

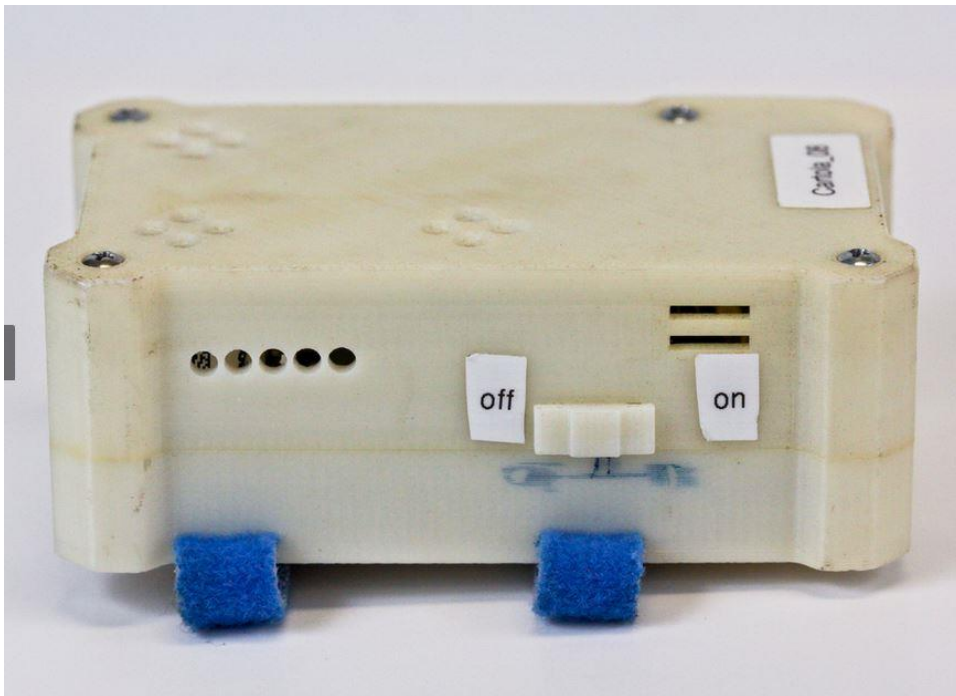


AirCasting Air Monitor

3. CairClip



4. CitiSense



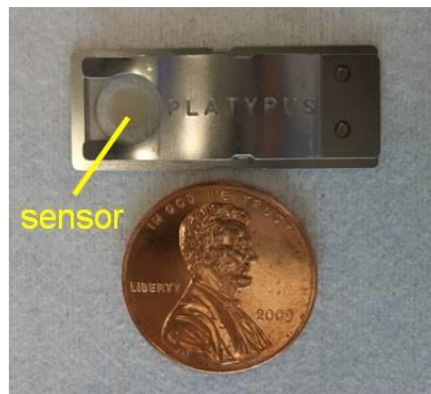
5. Dynamo



6. Platypus

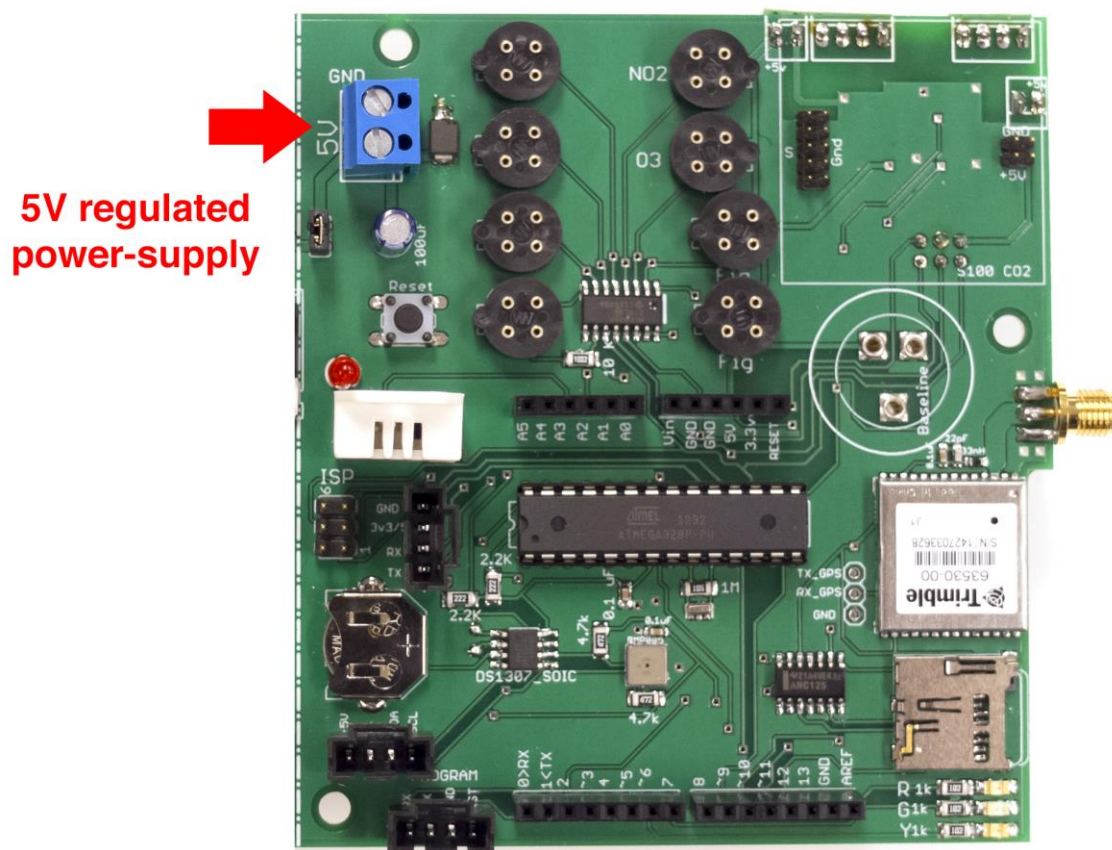
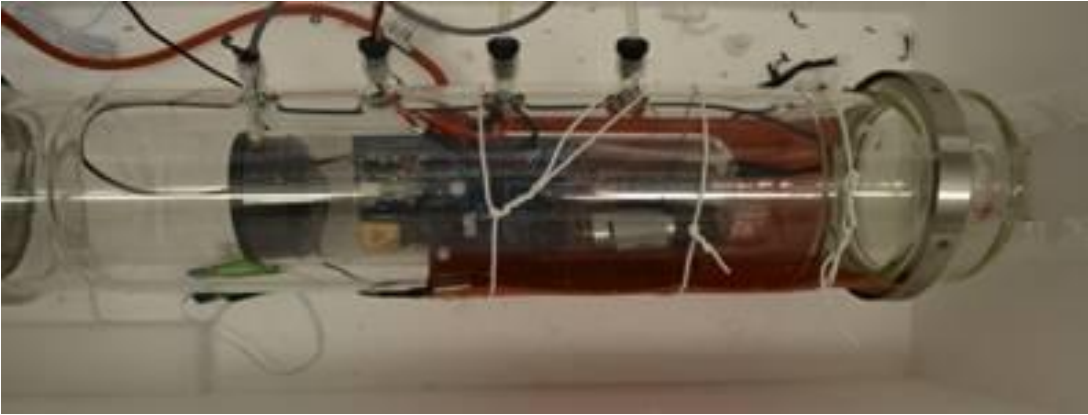


Platypus prototype handheld NO₂ monitor



The 5-mm diameter replaceable circular liquid crystal sensor element that slots into the Platypus prototype handheld NO₂ monitor

7. U Pod



Appendix C

List of Research Operating Protocols and Quality Assurance Project Plans Used in Support of This Research

SOP/ROP/QAPP No.	Title	Version
SOP-EHD-03-01	Operation and Maintenance of the TECO Model 49C UV O ₃ Analyzer	0
SOP-EHD-03-02	Operation and Maintenance of the TECO Model 43A Pulsed Fluorescence Sulfur Dioxide Analyzer	0
SOP-EHD-03-03	Operation and Maintenance of the TECO Model 42C Chemiluminescence NO _x Analyzer	0
SOP-4425-03-08(1)	Operation and Maintenance of the Omega RH 411 Digital Thermo-Hygrometer	0
Air Sensor ROP-PMRB-109.0	Research Operating Procedure for UPOD Air Sensor	0
Air Sensor ROP-PMRB-103.0	Research Operating Procedure for Cairclip O ₃ & NO ₂ Air Sensor	0
Air Sensor ROP-PMRB-106.0	Research Operating Procedure for the AGT Mobile Environmental Sensor	0
Air Sensor ROP-PMRB-101.0	Research Operating Procedure for AirCasting Air Monitor	0
Air Sensor ROP-PMRB-107.0	Research Operating Procedure for Platypus Technologies LC-NO _x Air Sensor	0
Air Sensor ROP-PMRB-104.0	Research Operating Procedure for CitiSense Air Sensor	0
Air Sensor ROP-PMRB-105.0	Research Operating Procedure for the Dynamo Air Sensor	0
QAPP-AB-12-03	ORD Sensor/Application Test Bed Challenge: Investigation of App/Sensor Response under Controlled Laboratory Conditions	0



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