VAISALA

WHITE PAPER

Compact air quality sensors and their use in local air quality management

Part 1: Technology

Contents

1 Background: The emergence of compact air quality sensors

The silent killer

Outdoor ambient air pollution continues to be one of the most significant global health risks. In 2017 ambient air pollution contributed to 2.9 million deaths worldwide (1). According to the World Health Organization, air pollution represents the biggest environmental risk to people's health (2).

Air quality has traditionally been monitored by government authorities using methods defined by, for example, EU Air Quality Directive or US EPA Federal Regulations. These methods typically have a high degree of accuracy and traceability which are obtained using refined analyzer technologies and calibration methodology. Due to the high cost and large size of these types of stations, they are typically installed in small quantities in limited locations rather than as networks which would characterize the air quality distribution in an area.

Since the early 2010s, a new category of air quality monitoring devices has appeared in the marketplace with great success. These compact air quality sensors have the potential to revolutionize air quality monitoring and management.

Technology background

Compact air sensors have emerged because two key sensing technologies reached a maturity level sufficient for envisaging operational instruments for field use: amperometric electrochemical sensors for detecting gaseous pollutants in ppb levels, and compact optical particle counters for detecting particles in the micron/submicron size range.

The first devices utilizing these technologies were typically portable experimental instruments used for pollution mapping in research and citizen science projects. Since the early days, the dominant product variety has changed from a portable hand-held device into a compact multiparameter fixed instrument, which is the sense in which we will be using the term "compact air quality sensor" in this paper.

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Product concept

Compact air quality sensors have many advantages over traditional analyzer-based reference air quality stations such as lower investment cost, smaller size and weight, and less labor required for deployment and maintenance. Thanks to their small footprint and low power consumption, the sensors are easy to place in areas such as the city infrastructure or near a pollution source. The tradeoff for compact sensors is their limited measurement performance, especially in demanding environmental conditions such as extreme or rapidly-changing humidity or temperatures.

During the last ten years, researchers and manufacturers worldwide have worked to understand, document and improve the measurement performance of the compact sensors.

Now that the sensors are becoming widely available with improved characteristics, users and regulators are still learning about the different aspects of their use in practice such as:

- how to best benefit from their easy deployment and relatively low cost
- how to optimally deploy and manage sensor networks
- how to best interpret and utilize their data

It is these aspects that this two-part white paper addresses.

2 Technology and performance

Electrochemical cell technology for gas sensing

Principle

The most widely used technology for ambient pollutant gas sensing in compact air sensors is the amperometric electrochemical technology. Electrochemical sensors utilize the reduction-oxidation reactions at a gas sensitized electrode surface of a galvanic cell to convert gas concentration to an electrical current running through the cell. The sensors are small, consume little power and are relatively low cost, making them compact and cost-efficient.

Image courtesy of Alphasense Ltd

Sensitivity and linearity

From a measurement quality standpoint, the advantage of electrochemical cells is their sensitivity. Due to the large absolute number of measurand gas molecules present in ambient air, even in ppb concentrations, the current from electrochemical reactions due to pollutants is relatively easy to measure with state-of-the-art electronics. Furthermore, by a proper design of the cell, the current flowing through the sensor can be made to depend linearly on the concentration.

The challenges in using electrochemical cells in field instrumentation lie in their susceptibility to environmental conditions such as temperature and humidity as well as their limited lifetime.

Temperature effect

Temperature influences both of the main mechanisms governing the operation of an electrochemical amperometric gas sensor: diffusion of gas molecules to the sensitized electrode and the consequent rate of electrochemical reactions that generate the signal current.

Without going too much into detail on the nature of these temperature dependencies, the fact that they do exist means that the signal from an EC gas sensor depends not only on gas concentration, but also on the sensor temperature in a relatively complex way. For a measurement instrument using EC gas sensors, this means that the temperature effects need to be considered and carefully compensated for in the signal processing algorithms and in calibrating the instruments.

Humidity effect

Ambient humidity is another environmental parameter that influences electrochemical gas sensors. In a relatively slow process, water molecules diffuse through the gas permeable membranes in the cell to reach an equilibrium. This does not have a significant effect on the sensor behavior in normal conditions, but in continuous extreme conditions there may be dramatic effects. In very dry conditions (below ~15 %RH), the electrolyte in the cell dries out, resulting in loss of signal. In prolonged very humid conditions, water may diffuse into the cell in excess amounts and cause the electrolyte to leak out, damaging the cell.

Transients

Properly designed instruments perform well with steady-state and slow variations of temperature and humidity. However, in transient situations of rapidly-changing temperature and humidity, the effects are far more difficult to model in signal processing algorithms and may temporarily cause errors in measurement. A well-known example of a transient effect is a peak in electrochemical cell current signal caused by a step change in ambient humidity.

Selectivity

The selectivity of electrochemical sensors to the desired gas is reached by introducing gas sensitized layers to the electrodes, whose reaction chemistry is optimized for the target gas. In some cases, known interfering gases may also be removed from the measured gas with specific scrubbers introduced in the sensor. However, as is the case with chemical sensor in general, the selectivity of EC cells is limited and manufacturers typically list the most common cross-sensitivities in sensor datasheets. Some typical cross sensitivities encountered are the cross sensitivity between NO_2 and O_3 sensors, and a negative effect of high NO_2 concentrations to SO2 sensors.

Maintenance

Electrochemical gas sensors resemble household batteries in the sense that they are consumable items that need to be replaced after their service life has ended. This is because the chemical reactions taking place in their operation deplete the materials (electrodes and electrolytes) inside the sensor. The service life of the sensors depends on cumulative exposure to gas concentrations: The sensors are used up more rapidly in high concentrations than in low ones. A typical lifespan of an electrochemical gas sensor is 1-3 years depending on the sensor type and the pollutant levels.

Optical particle counters for particle measurement

Principle

By far, the most common method for measuring particulate matter ($PM_{2.5}$, PM_{10}) in compact air quality sensors is optical detection based on light scattering from particles. In these detectors, a focused light beam from a semiconductor laser or an LED illuminates a sample air flow and the light scattered by the particles in the air sample is measured by a photodetector.

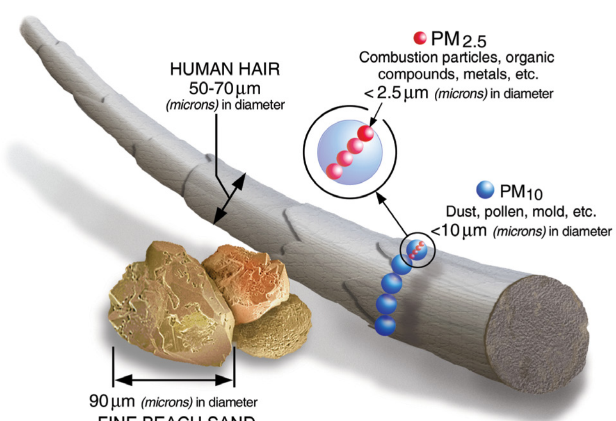
In a typical arrangement, the flow is generated by a pump or fan and the photodetector is placed at a forward or right angle with respect to the light beam. A signal processing algorithm then processes the signals from the photodetector to yield the mass of the particles in the known volume of sampled air.

Signal processing

In optical particulate sensing, there are two main principles according to which the sensors operate.

In the nephelometer principle, the raw signal in the sensor is the net total current caused by the scattered light on the photodetector. The measured current is then converted into particle mass concentration with calibration factors. Using this principle, the electronic design of the readout is relatively simple, but the amount of information obtained from the measured particles is minimal.

In the particle counting principle, the signals from individual particles (in the form of tiny flashes of light) are measured and analyzed with a pulse height analyzer. The signal processing circuitry in this method needs to be more advanced to cope with high pulse rates for the pulse height analysis. The advantage of the counting principle is that far more information like the number and size of particles is available, making a more accurate estimate of particle mass concentration possible.



Source: US EPA

Optomechanics

A benefit of optical particle sensors is that their basic construction is relatively simple, so they can be built smaller using fewer components. However, while the basic construction is simple, the design must be carefully optimized to ensure efficient detection of all particles and minimize contamination by particles adhering to the optical and other surfaces. The sensor's optical and mechanical design also has an important effect on unit-to-unit reproducibility and long-term stability.

Particle mix and size

A limitation of optical particle sensing is that the amount of light scattering from particles does not primarily depend on the quantity of interest (i.e., particle mass), but there are many factors affecting the way the scattered and detected light signal corresponds to particle mass. Examples include the optical properties, physical shape and material density of the particles.

The sensors are typically calibrated with particles of known properties such as spherical polystyrene bead particles or so-called Arizona test dust, but because of the effects mentioned above, the readings from an optical particle sensor inevitably vary by the nature of the particle mix being measured.

Due to the physics of the scattering process, the amount of scattered light gets extremely small as the particle size falls below the wavelength of the light used for the measurement. This limits the minimum particle size that can be measured with compact optical particle sensors to typically 0.4-0.6 micrometers. A consequence of this is, for some applications and particle sources like fine particles from car exhaust or smoke from forest fires, the compact particle sensors are not optimally suited.

Temperature & humidity

OPC performance is typically very stable with varying temperatures. The main effect from ambient conditions to OPC readings is from humidity, especially in very high levels close to condensing conditions when atmospheric moisture may absorb and condense on particles, and this way increase their optical diameter. This enhances light scattering from the particles and results in high readings from the sensor, although the dry mass of particles remains unchanged. In more expensive and bulky systems this is addressed by heating the sample inlet to get rid of excess moisture, but in compact sensors this is often not feasible.

Field performance

Co-location study

A widely used practice for evaluating the field performance of compact air quality sensors is to co-locate them with reference analyzers and compare the readings. For a visual interpretation of the agreement between the two readings, see the time series graph depicted in Figure A (below).

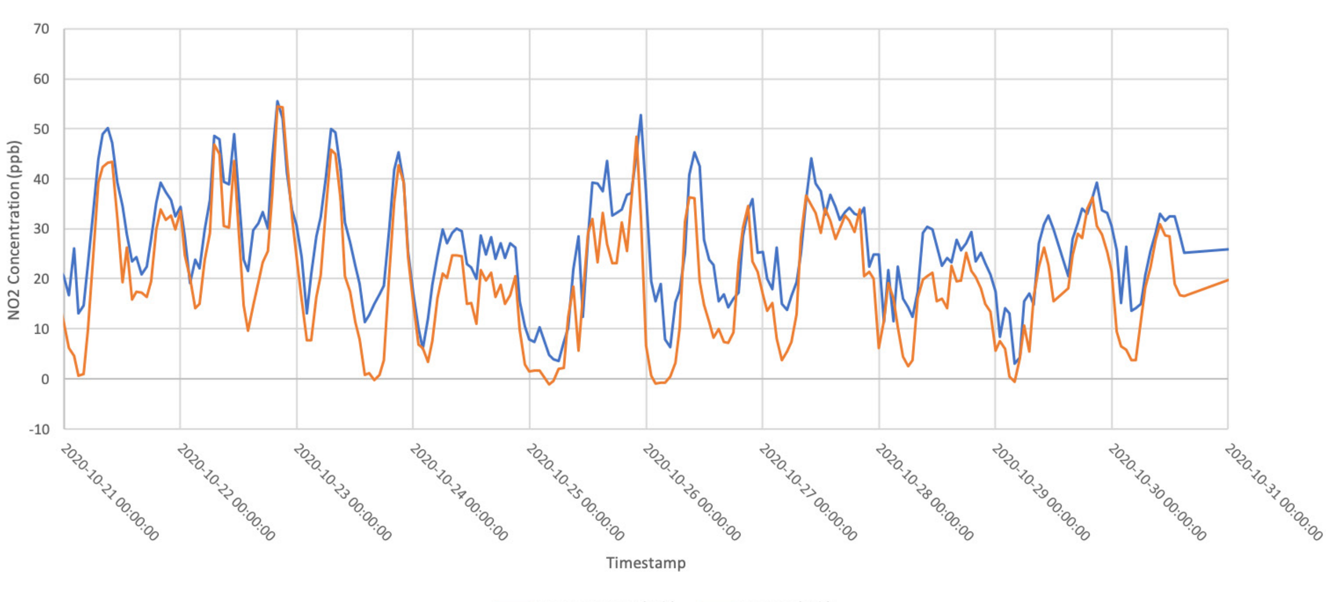


Figure A: Time series graph

Regression and R2

In order to quantify the agreement, it is common to perform a statistical regression analysis of the correlation between the hourly average readings from the sensor under study and the reference analyzer. The analysis yields the linear regression coefficients linking the two variables as well as the statistical R2 coefficient of determination between them.

The R2 coefficient, often somewhat inaccurately referred to as correlation factor, describes how well the sensor readings correlate with those of the analyzer, whereas the linear regression coefficients indicate systematic offset- and gain-like linear differences between the sensor and analyzer.

R2 interpretation

As a rule of thumb: An R2 number above 0.6 is considered fair, above 0.7 good, above 0.8 very good and above 0.9 excellent. However, one should be careful in interpreting the R2 numbers since the conditions during the data collection period have an important effect on the results. In general, tests in stable environmental conditions with widely varying concentrations produce better R2 values than tests in widely varying environmental conditions with persistent low concentrations.

Longer test periods also tend to lower the obtained R2 value. For a meaningful comparison, a test period of 1-2 months with at least occasional significant variation in measured concentration is needed.

The statistical analysis is often documented in the form of a graph where hourly average readings from the sensor are drawn against the analyzer readings averaged over the same hours, as illustrated in Figure B (above).

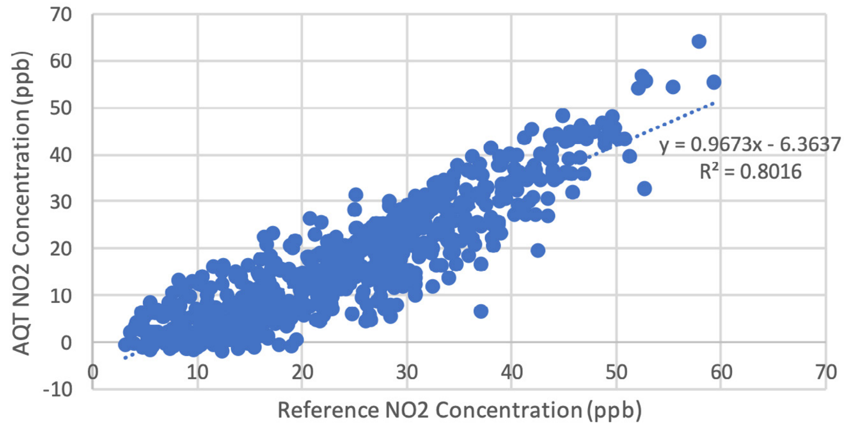


Figure B: Scatter graph illustrating the correlation between sensor and reference readings

Correction equation

Results from a co-location study can also be used to perform a linear correction to the sensor data with the obtained regression coefficients and make the sensor response optimally match that of the reference analyzer. This may be particularly relevant for the particulate measurements, where this step can be seen as a way to adapt the OPC response to the local particle composition and compensate for the particle mix effects described in the previous section.

Regulatory aspects

Human health and well-being are the primary motivators for air quality monitoring in cities. The current mechanism to guarantee healthy air is through international or national legislation that defines limiting values for key harmful substances and requires local authorities to ensure compliance. The role of regulatory air quality monitoring is then to provide proof that pollutant concentrations are below the defined limits.

Questions often arise on the regulatory status of compact air quality sensors. Are they approved or certified by the EPA or EU for proving compliance? Which norms or standards do they fulfil? The fact is, there is currently very little normative material pertaining to compact air quality sensors.

EU AQ Directive

The EU Air Quality Directive 2008/50/EC recognizes the concept of "indicative measurements," which refers to measurements methods that have a less stringent accuracy requirement than the reference or reference equivalent methods (referred to as "fixed measurements" in the Directive). According to the Directive, indicative measurements can be used in combination with fixed measurements for air quality assessment in areas with lower pollution levels as defined in the Directive. (3)

CEN/TC 264 WG42

In European legislation, technical requirements for performing fixed measurements are documented in EN standards for reference methods (4-9), and in the guide for demonstrating the equivalence to the reference methods for the reference equivalent methods (10). The current legislation does not, however, include a technical specification or standard for indicative measurements. This technical specification is currently being developed in a CEN working group (CEN/TC 264 WG42) and the first part of the specification is expected for publication at the end of 2021.

UK, France

National-level activity towards a certification for air quality sensors exists also in France, managed by the research and metrology organizations Ineris and LNE. A rare piece of existing legislation is the UK MCERTS standard for indicative particle measurements (11).

US CFR40

In the United States, the legislation governing air quality monitoring (CFR40 Part 53 and CFR40 Part 58) does not include a definition or classification for compact air quality sensors. The US EPA has, however, taken an active role in testing commercially available sensor products and creating guidance for use in local air quality management.

AQ-SPEC

A test center dedicated for testing compact air quality sensors (Air Quality Sensor Performance Evaluation Center, AQ-SPEC) has been established at the South Coast Air Quality Management District in California. The AQ-SPEC has a standard sensor evaluation procedure that they apply to commercially available sensors and publish the results on their website (12).

ASTM

A US performance standard document for compact air sensors is in development by the ASTM as the working item WK64899 "New Practice for Performance Evaluation of Ambient Air Quality Sensors and Other Sensor-Based Instruments."

US EPA

The US EPA (Office of Research and Development and Office of Air Quality Planning and Standards) is actively testing and evaluating air sensors and has prepared a significant amount of supportive material for compact air quality sensor users. This material is available on their website (13).

1. HEI, Health Effects Institute. State of Global Air, 2019. ISSN 2578-6873.
2. WHO, World Health Organization. Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease, 2016. ISBN 978 92 4 151135 3.
3. Directive 2008/50/EC of the European Parliament and of the Council, 21.5.2008.
4. EN 14212:2005 'Ambient air quality— Standard method for the measurement of the concentration of sulphur dioxide by ultraviolet fluorescence'.
5. EN 14211:2005 'Ambient air quality — Standard method for the measurement of the concentration of nitrogen dioxide and nitrogen monoxide by chemiluminescence'.
6. EN 12341:1999 'Air Quality — Determination of the PM10 fraction of suspended particulate matter — Reference method and field test procedure to demonstrate reference equivalence of measurement methods'.
7. EN 14907:2005 'Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter'.
8. EN 14626:2005 'Ambient air quality — Standard method for the measurement of the concentration of carbon monoxide by non-dispersive infrared spectroscopy'.
9. EN 14625:2005 'Ambient air quality — Standard method for the measurement of the concentration of ozone by ultraviolet photometry'.
10. 'GUIDE TO THE DEMONSTRATION OF EQUIVALENCE OF AMBIENT AIR MONITORING METHODS', Report by an EC Working Group on Guidance for the Demonstration of Equivalence, January 2010.
11. 'Performance Standards for Indicative Ambient Particulate Monitors', Environment Agency, August 2015, Version 3.
12. http://www.aqmd.gov/aq-spec
13. https://www.epa.gov/air-sensor-toolbox

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