PAS 4023:2023

Selection, deployment and quality control of low-cost air quality sensor systems in outdoor ambient air – Code of practice



Department for Environment Food & Rural Affairs

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Foreword

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It has been assumed in the preparation of this PAS that the execution of its provisions will be entrusted to appropriately qualified and experienced people, for whose use it has been produced.

Presentational conventions

The provisions of this document are presented in roman (i.e. upright) type. Its recommendations are expressed in sentences in which the principal auxiliary verb is "should".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

The word "should" is used to express recommendations of this PAS. The word "may" is used in the text to express permissibility, e.g. as an alternative to the primary recommendation of the clause. The word "can" is used to express possibility, e.g. a consequence of an action or an event.

Notes and commentaries are provided throughout the text of this document. Notes give references and additional information that are important but do not form part of the recommendations. Commentaries give background information.

Where words have alternative spellings, the preferred spelling of the Shorter Oxford English Dictionary is used (e.g. "organization" rather than "organisation").

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Introduction

Recent developments in air quality monitoring have resulted in new sensor systems that potentially provide an informative low-cost addition to reference methods. Such sensor systems are expected to allow air pollution monitoring to be performed at a lower cost and with a higher spatial density than is possible with the current reference methods. They also allow for new source apportionment and calibration methodologies, when coupled with spatial information, to provide a much better understanding of an individual's or group's exposure to air pollutants.

The potential advantages of low-cost air quality sensor systems include the following:

- small footprint making them easily deployable in the urban environment;
- larger area coverage than fixed point measurements if a network approach is implemented and improved spatial and temporal resolution; and
- potential of continuous calibration through co-location with reference style analysers and a network calibration.

For these advantages to be exploited, it is important that robust quality assurance is performed on the data produced.

This PAS has been developed to provide recommendations and guidance to users to:

- select sensor systems appropriate for their monitoring needs;
- deploy sensors in a way that promotes representative sample collection; and
- undertake the quality assurance (QA) processes to generate good quality data from these systems.

Additional information is also provided in four annexes as follows:

- Possible monitoring scenarios (Annex A);
- Examples of network calibrations (Annex B);
- Case studies on improving the comparability of sensor systems (Annex C); and
- Sensor technologies and performance issues (Annex D).

The sensor systems are based upon several principles of operation, including:

- electrochemical for NO_2, NO, SO_2, CO and O_3;
- light scattering optical particle counter for PM_{10}, $PM_{2.5}$ and PM_1; and
- non-dispersive infrared (NDIR) for CO_2.

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The sensor systems can also continuously monitor air pollution, with fast response times ranging between a few tens of seconds to a few minutes, but presently with a reduced measurement accuracy (higher uncertainty) and lower precision.

NOTE 1 *The term "low cost" refers to the initial purchase price of a single air quality sensor system and is not an indicator of measurement accuracy. The cost is dependent on the number of pollutant sensors employed and users implementing a large network of systems. The cost of necessary co-location deployments, quality checking and adjustment can be substantial. Examples of these costs are sensor replacement, installation, removal, consent issues/legal, power access, co-location charges and data processing. Most importantly, the purchase price might not account for additional ongoing charges for access to the measurement data. Whilst the UK has performance standards for reference quality instruments, and guidance for monitoring under Local Air Quality Management (LAQM) application, there is no formal code of practice for the evaluation, deployment and use of low-cost sensors and networks composed of these sensors.*

NOTE 2 *Although "low-cost" air quality sensor systems have advanced significantly, there are currently no validated published documentary standards against which to judge their performance and therefore cannot be used for official compliance reporting against limit values. PD CEN/TS 17660-1, however, provides information on how to test the performance of these types of sensor systems for gaseous species.*

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1 Scope

This PAS provides recommendations for the selection, deployment, maintenance and quality assurance of low-cost air quality sensor systems as standalone units or as part of a network, for the measurement of outdoor ambient air as suited to their application and desired purpose. This includes systems that are static in position and semi-permanent in placement.

This PAS covers air quality sensor systems which measure one or more of the following gaseous or particulate pollutants:

- nitrogen dioxide (NO_2);
- oxides of nitrogen (NO_x);
- nitric oxide (NO);
- ozone (O_3);
- sulfur dioxide (SO_2);
- carbon monoxide (CO);
- carbon dioxide (CO_2); and
- particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) in outdoor ambient air.

This PAS is intended for use by those aiming to monitor and report on air quality through the implementation of low-cost air quality sensor systems, including policy makers, local authorities, environmental health officers, citizen scientists, industrial users, sensor system manufacturers and suppliers, academics, researchers, and those with an interest in air quality quantification and improvement.

NOTE 1 *The PAS would be beneficial to those involved in delivering Local Air Quality Management (LAQM). Technical guidance on measurements for LAQM purposes is given in TG22 [1].*

This PAS does not cover:

- statutory legal reporting of data against the national air quality objectives;
- passive diffusive tubes, e.g. Palmes diffusion tubes;
- pumped sorption tubes;
- total volatile organic compound (VOC) low-cost sensors;
- single hydrocarbon/VOC low-cost sensors;
- sensors providing an indoor air quality index (IAQ);

  NOTE 2 *This PAS acknowledges the use of sensors for measuring indoor air quality but provides no formal guidance or recommendations for making occupational health measurements or other indoor air measurements.*

- portable hand-held or wearable sensor systems;
- sensor systems used in mobile applications, both ambient and indoor air;
- the provision of intellectual property for the air quality sensor system specific technologies or specific products;
- the collection format and storage of data obtained from the sensor system, including any human interventions, such as for the analysis and interpretation of results;
- access to the data and the data format;
- making reliable measurements in confined spaces, including subways, tunnels or underground railways; and
- the use of air quality sensor systems for compliance monitoring and reporting, including demonstrating adherence to pollutant limit values or targets enshrined in legislation.

  NOTE 3 *Examples of such legislation include the Air Quality Standards Regulations 2010 [2], the Air Quality Standards (Scotland) Regulations 2010 [3], the Air Quality Standards (Wales) Regulations 2010 [4], the Air Quality Standards (Northern Ireland) Regulations 2010 [5] and the Environmental Targets (Fine Particulate Matter) (England) Regulations 2023 [6].*

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2 Normative references

There are no normative references in this PAS.

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3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this PAS, the following terms and definitions apply.

3.1.1 algorithm

mathematical set of rules specifying how a data set responds to changes in input conditions

3.1.2 ambient air

outdoor air in the troposphere, excluding workplaces where provisions concerning health and safety at work apply and to which members of the public do not have regular access

***NOTE** This excludes workplaces as defined by Directive 89/654/EEC [7].*

[SOURCE: Directive 2008/50/EC, modified] [8]

3.1.3 calibration

operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

***NOTE 1** In the measurement procedure, data delivered by a sensor are compared with a calibration standard of known accuracy.*

***NOTE 2** A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.*

***NOTE 3** Calibration is not to be confused with adjustment of a measuring system, often mistakenly called "self-calibration", nor with verification of a calibration.*

***NOTE 4** Often, the first step alone in the above definition is perceived as being calibration.*

[SOURCE: JCGM 200:2012©, **2.39**]

3.1.4 co-location

action of placing a sensor system side by side or in close proximity to another sensor system or reference method to obtain a comparison

3.1.5 detection limit

lowest signal, or the lowest corresponding quantity to be determined from the signal, which can be observed with a sufficient degree of confidence or statistical significance

***NOTE** Depending on the requirements, the sufficient degree of significance is normally 95% or 99%.*

3.1.6 drift

continuous or incremental change over time in reported measurement of concentration, due to changes in properties of a sensor system

***NOTE** The drift is related neither to a change in a quantity being measured nor to a change of any recognized influence quantity.*

[SOURCE: PD CEN/TS 17660-1:2021©, **3.17**]

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3.1.7 metadata

set of data that gives information about other data

NOTE *A non-exhaustive set of examples of metadata include:*

- *precise deployment location of sensor system;*
- *quality information on the uncertainty of a dataset, flags indicating faults in the dataset, calibration data and any ongoing audit data, sensor health data;*
- *sensor information such as the system manufacturer, model type number and history, and the measurand and its units;*
- *ancillary data consisting of other datasets required for the measurements, namely environmental conditions of temperature and pressure or values of interfering quantities, e.g. relative humidity;*
- *configuration information such as a time stamp of the measurement, whether pollutant data is raw or processed, and site information, e.g. sampling system, sample point details (height, flow rate); and*
- *other information to support auditing such as the local site operator identifier or contact point for the data set, and any quality standards or protocols which have been followed in the measurements.*

3.1.8 network

more than one sensor system where data is to be compared between those sensors spatially and/or temporally, or where a common calibration is applied to those sensors

3.1.9 noise

irregular fluctuations that accompany a signal but are not part of the signal and have the potential to obscure it

3.1.10 reference method (RM)

measurement method(ology) which, by convention, gives the accepted reference value of the measurand

3.1.11 sensor

individual sensor, chemical cell or physical unit that produces an analytically useful signal by detecting or measuring the analyte

[SOURCE: PD CEN/TS 17660-1:2021©, **3.2**]

3.1.12 sensor system

single integrated set of hardware that uses one or more sensors to detect and/or measure a chemical concentration or quantity that is able to supply real time measurements after calibration

[SOURCE: PD CEN/TS 17660-1:2021©, **3.3**]

3.1.13 traceable measurement

property of a measurement where the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty

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3.2 Symbols

For the purposes of this document, the following symbols apply.

CO	carbon monoxide
CO_2	carbon dioxide
CF	calibration factor
D_{rate}	drift rate
H_2S	hydrogen sulfide
mW	milliwatt
NH_3	ammonia
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
O_3	ozone
PM_{10}	particulate matter with an aerodynamic diameter <10 µm
$PM_{2.5}$	particulate matter with an aerodynamic diameter <2.5 µm
PM_1	particulate matter with an aerodynamic diameter <1 µm
SO_2	sulfur dioxide
µg/m^3	micrograms per cubic meter
µmol	micromole
µmol/mol	mole fraction of 1 x 10^6 mol per mol
mol	mole
nmol	nanomoles
nmol/mol	mole fraction of 1 x 10^9 mol per mol
t	time

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4 Performing a measurement campaign

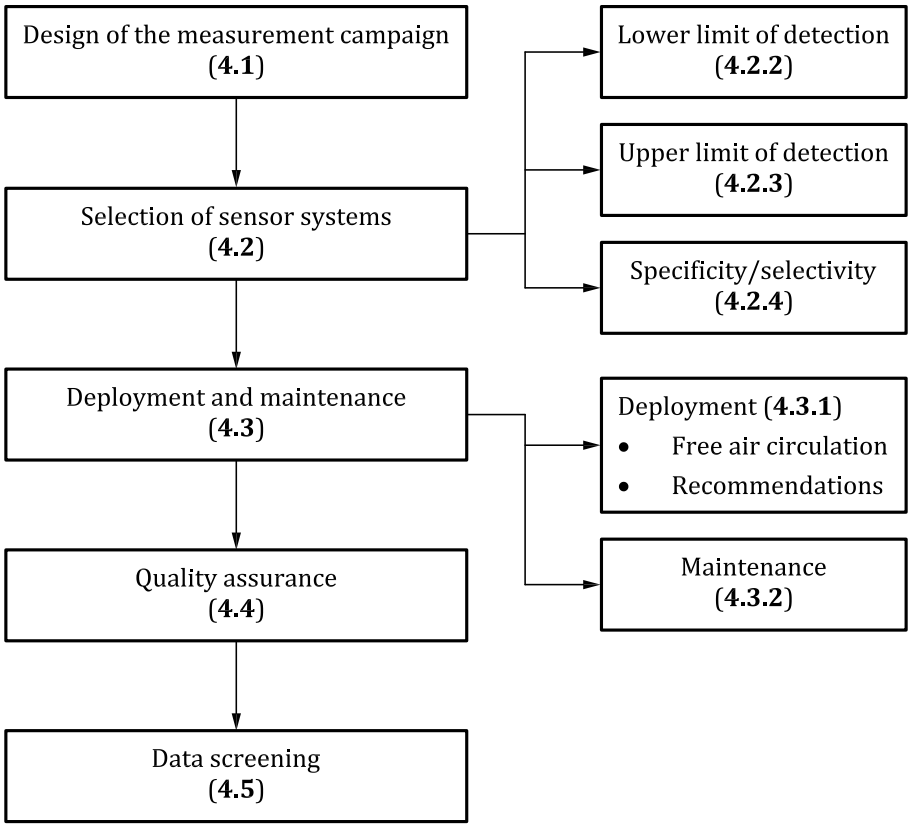
COMMENTARY ON CLAUSE 4

Low-cost air quality sensor systems have become increasingly popular in the last 5 years or more for measuring air pollution concentrations due to their reduced cost compared to reference method style instrumentation. This allows users to make measurements at many more locations with a view to gaining a better understanding of local conditions and population exposure.

Although sensor system measurements are generally less accurate than reference measurements, due to the technology used and difficulties with direct calibrations, these systems have an important role in assessing air quality.

This clause provides recommendations and guidance on performing a measurement campaign for low-cost air quality sensor systems and provides an overview of the steps users need to implement to provide their final data set. The steps are presented in a schematic diagram in Figure 1 and the following sub-clauses provide information on each step.

Figure 1 – Steps to performing a measurement campaign



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4.1 Design of the measurement campaign

The design of the measurement campaign should be based on the aims and potential desired outcomes and should be documented for future reference.

NOTE 1 *For example, documented procedures can facilitate auditing.*

The following should be taken into account in the selection and operation of low-cost sensor systems over the measurement campaign:

a) pollutants to be measured;

b) duration of the measurement period;

c) range of expected pollutant concentrations;

d) specificity/selectivity of sensor systems;

e) deployment and maintenance;

f) required accuracy and precision to correctly assess the magnitude of any pollutant concentration(s);

g) suitable time response for the proposed data averaging period;

h) required long-term stability (lack of drift or correction of drift) required to demonstrate a quantifiable change in pollutant concentration(s);

i) level of quality assurance; and

j) final use of collected data.

NOTE 2 *The above list is not exhaustive, and the user may need to check whether there are additional requirements, including metadata, if the measurements are to be presented to external bodies.*

NOTE 3 *If local meteorological data are available, this can aid the understanding of possible pollution sources but is not essential for every measurement campaign.*

NOTE 4 *The ability to make more measurements does not necessarily lead to a better understanding of air quality, unless sensors are comparable, have a time stable response to air pollutants and are operated under a robust quality control and calibration methodology. Quality control is necessary in order to ensure that the uncertainties of the sensor measurements are well understood during extended continuous monitoring periods.*

NOTE 5 *Annex A provides a schematic diagram giving an overview of possible monitoring scenarios.*

4.2 Selection of sensor systems

4.2.1 General

The sensor system selected should be suitable for the measurement requirement.

NOTE 1 *Selection of the appropriate sensor system can be informed by consulting literature provided by manufacturers and published reports/peer-reviewed scientific papers. Air quality experts can also be consulted.*

The selected sensor system should be capable of measuring the expected pollutant concentration range, including being above the limit of detection.

Data averaging periods should not be shorter than a sensor's response time, as this can lead to non-independent measurements being recorded and an increase in measurement uncertainty.

NOTE 2 *Manufacturers publish the range of each sensor, usually as 0 µg/m^3 to X µg/m^3, and often state a level of accuracy under ideal conditions over that range.*

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NOTE 3 *The suitability of sensor systems for monitoring ambient pollutant concentrations is best demonstrated through formal type testing. For gaseous measurements, the UK performs formal type testing to PD CEN/TS 17660-1 through the MCERTS performance standards for ambient monitoring equipment [9] and for particulate matter measurements through the MCERTS performance standards for indicative ambient particulate monitors [10]. However, currently there are no accredited suppliers of this type testing service. It is the responsibility of the manufacturer to arrange for sensor systems to be type-tested if relevant accreditations are required for their products.*

NOTE 4 *Users can perform their own performance evaluation, either based on the procedures described in the type testing documents, or their own design. If users perform their own evaluation, then Bland-Altman analysis is a useful tool in addition to linear regression against a reference analyser. These analysis methods are discussed in Defra's Low-cost air quality sensors – Test and experimental procedure development [11]. It is recommended that any user performance evaluation is fully documented for future reference.*

NOTE 5 *The lack of any performance evaluation and/or robust calibration and quality assurance procedures can lead to data of poor quality that is not suitable for evaluating air pollution concentrations.*

4.2.2 Lower limit of detection

NOTE 1 *The lower limit of detection is determined by the minimum sensitivity and the "noise" of the measurements close to a zero concentration.*

When measuring locations with very low concentrations (where the detection limit of the sensor can be more important than the sensor calibration) a sensor with a detection limit lower than expected concentrations should be selected.

NOTE 2 *For example, if concentrations of 10 µg/m^3 are expected then use of a sensor with a minimum detection limit of 1 µg/m^3 would be suggested, if possible.*

NOTE 3 *The minimum range of a sensor is different from the lower limit of detection.*

4.2.3 Upper limit of detection

NOTE 1 *All sensors have a maximum concentration that they can measure before the measurement system stops responding to increasing concentrations or the uncertainty is greater than the manufacturer's specification.*

A sensor with an upper limit of detection (range) that incorporates likely high pollution events should be selected.

NOTE 2 *This can be up to two orders of magnitude (100x) greater than average daily concentrations.*

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4.2.4 Specificity/selectivity

*COMMENTARY ON **4.2.4***

Sensors respond not only to the pollutant that they have been identified to measure but can also respond to other pollutants that are present. These other pollutants might or might not be of interest to the user. These other pollutants that the sensor responds to are called "interfering species".

Interference data supplied by the manufacturer should be consulted when selecting suitable sensors. If the aim is to implement a higher level of quality assurance to determine the effect of interfering species, then parallel measurements should be made with a reference quality analyser with proven high specificity to the target substance in a real-world location, or an atmospheric test chamber.

***NOTE 1** If the sensor system is measuring multiple pollutants, then these measurements can be used to identify possible interferents. As an example, ozone (O_3) is known to interfere with nitrogen dioxide (NO_2) sensors, and although some sensor manufacturers use chemical filters to reduce this, ozone at high levels might still have a detrimental effect on NO_2 readings. Ozone levels can vary significantly from day to night and from season to season, requiring monitoring of any variation in sensor performance which might be related to this.*

If making measurements close to industrial emissions, it should be determined if these emissions are likely to cross-interfere with the sensor system's measurements.

***NOTE 2** Specific industrial emissions (which frequently include VOCs) might not be included in a sensor manufacturer's list of interfering gases.*

4.3 Deployment and maintenance

*COMMENTARY ON **4.3***

This clause provides general recommendations for the deployment and maintenance of sensor systems. Information on site classification and sampling points for legislative monitoring is available in EU Directive 2008/50/EC, Annex III [8].

4.3.1 Deployment

Sensor systems should be deployed at a monitoring location in accordance with the manufacturer's instructions in such a way that their normal operation is not compromised.

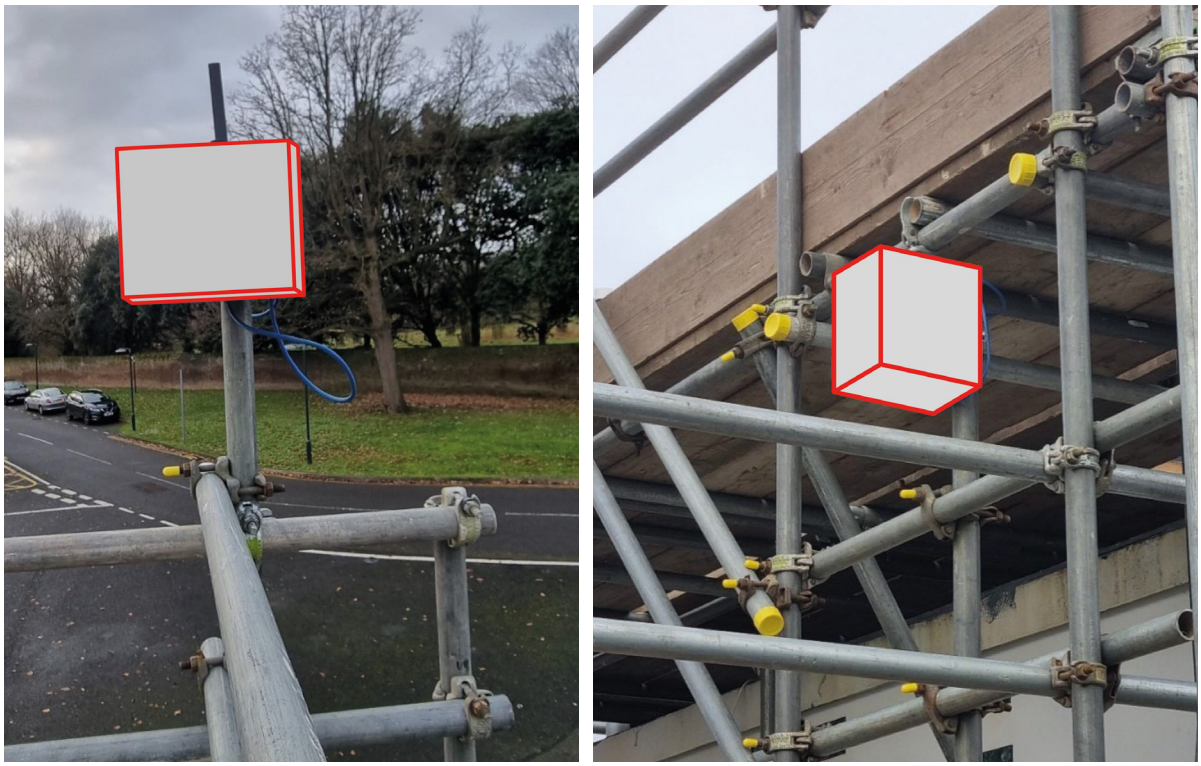
***NOTE 1** The deployment location of a sensor system has an influence on the quality of data that can be acquired, and a poor site selection will be detrimental to the quality of the measurements taken.*

Sensor systems should be deployed in an area that has free air circulation so that the sensors respond to changes in ambient pollutant concentrations and are representative of the local population exposure.

***NOTE 2** Figure 2 provides examples of a sensor system mounted in a location with free air circulation and in a location with stagnant air/poor air circulation. The sensor system in Figure 2b) is partially under an overhanging platform and the whole system is in the wind shadow of the adjacent building. Please note that the red outline in Figure 2 to Figure 5 and Figure 7 indicates sensor systems.*

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Figure 2 – Sensor system deployment



a) Area of free air circulation

b) Area of stagnant air/poor air circulation

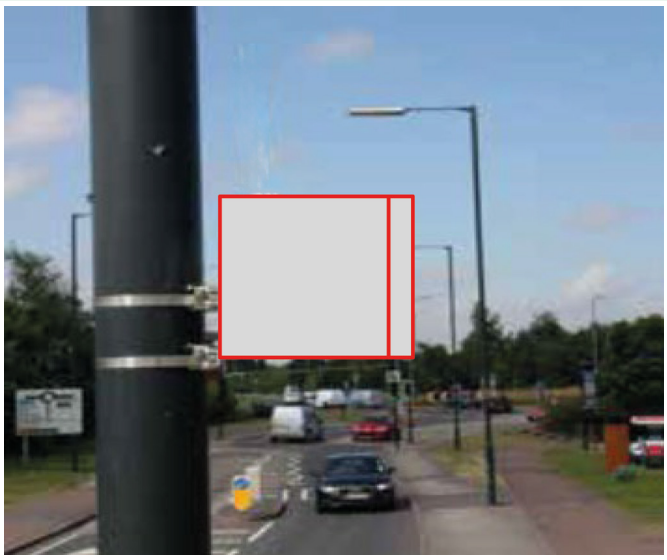
To reduce the effect of wind shadowing from trees and buildings, the sensor system should be placed at least one tree/building height away from the obstruction. There should be at least 180° of unobstructed air flow at the sensor and ideally 270° or more.

Sensor systems should be located, where possible, in the breathing zone (1 m to 4 m above the ground) for roadside and urban background sites.

NOTE 3 *Sensor systems may be mounted higher off the ground to prevent vandalism (see Figure 3).*

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Figure 3 – Sensor system deployed in an area of free air circulation and reduced risk of vandalism



Measurements should be made on both sides of the road in a street canyon to aid understanding of human exposure and to take into account that the concentration profile can vary with wind direction.

NOTE 4 *The Greater London Authority has provided a Guide for monitoring air quality in London [12], which contains information on site classifications, considerations when choosing monitoring locations and selecting low-cost sensors.*

NOTE 5 *The enhanced air sensor guidebook [13], published by the United States Environmental Protection Agency (US EPA), contains information on low-cost sensor selection, performance evaluations, sensor co-locations and standard operating protocols for low-cost sensor systems.*

Sensor systems should not be deployed in areas with stagnant air/poor air circulation, including:

a) too close to a vertical (wall/building facade) or horizontal (overhanging roof/roof below sensor system) surface;

   NOTE 6 *See Figure 4.*

b) in the wind shadow of trees or other obstacles to the prevailing wind; and

   NOTE 7 *See Figure 5.*

c) subways, tunnels, underpasses, and other confined spaces or areas with reduced ventilation (e.g. courtyards).

NOTE 8 *Sensor systems deployed in areas of stagnant air/poor air circulation do not receive a continuous fresh supply of ambient air and therefore do not adequately track changes in concentration (unless the air quality at these locations is the specific target of the measurement campaign).*

Sensor systems should also not be deployed:

1) next to central heating exhaust vents/flues, air conditioning outlets, vegetation, and direct emissions from industrial outlets; and

2) in areas of strong electromagnetic radiation fields (as this can result in reduced performance) including mounting on a conductor (metal street lighting etc.) if it has been shown that this can cause radio frequencies that have a detrimental effect on sensor system performance.

NOTE 9 *In extreme cases, poorly designed sensor power supplies suffer from induced interfering radio frequency (RF) signals.*

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Figure 4 – Poor deployment location with a wall too close to the sensor system



Figure 5 – Poor location with plants too close to the sensor system



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Sensor systems should be allowed to acclimatize as per the manufacturer's instructions before the data are used for performance evaluation or air quality measurements.

If the sensor system is being used in locations with quickly changing concentration profiles, then the sensor system should be set to sample continuously to provide representative measurements, or the effect of subsampling (time coverage less than 100%) should be assessed and findings documented.

Sensor deployment should limit as far as is possible the exposure of the sensor to rapid changes in temperature and humidity, as this can affect sensor performance.

When solar panels are used to power sensors systems, they should be aligned correctly for the latitude of the location so they receive sufficient sunlight throughout the year to power the system, especially in the winter. Solar panels should not be shaded but receive direct sunlight for the majority of daylight hours to enable them to operate efficiently.

In addition to the provisions detailed above, the following should be taken into account when deploying sensor systems:

i) secure environment to minimize the risk of vandalism/theft;

ii) safe access to allow for ongoing maintenance;

iii) availability of electrical power and telephone communications and avoiding areas of poor mobile phone network coverage;

NOTE 10 *Electrical installations can be expensive as they require the use of trained electricians.*

iv) visibility of the site in relation to its surroundings, taking into account local sensitivities or relevant stakeholders;

NOTE 11 *Some suppliers use relatively noisy pumps with their PM sensors, which might cause complaints from residents.*

v) the health and safety of the public and operators; and

vi) any planning permission requirements.

The deployment of each sensor system should be fully documented.

NOTE 12 *Table 1 provides a guide to the information that can be recorded. Documentation can allow for independent audit.*

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Table 1 – Site deployment information

Parameter	Metadata
Site name	
Installation date	
Location	Latitude: Longitude: OS reference:
Classification[1)]	Kerbside/Roadside/Urban background/Suburban background/Rural background/Industrial
Pollutants measured	NO_2/NO/NO_x/SO_2/CO/CO_2/O_3/PM_1/$PM_{2.5}$/PM_{10}
Security/risk of vandalism/access	Details
Access to street furniture	
Electricity supply	
Co-located with reference analyser	AURN/LAQM/other/none Details:
Ease of mounting sensor unit	
Site accessibility	
Height from ground level in metres	
Geographic concerns	None/street canyon/overhanging bushes etc. Details:
Photograph of location	Map of location:
NOTE *Where the recommendations on deployment have not been followed, then these deviations can be recorded in this table under geographic concerns.*	

1) Available at https://uk-air.defra.gov.uk/networks/site-types.

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4.3.2 Maintenance

The manufacturer's instructions should be followed with regards to maintenance schedules and sensor lifetimes. Diagnostic outputs (e.g. battery voltages) should be used, if available, to inform the operational health/status of sensor systems.

NOTE 1 *Many sensor systems report status information to allow the user to assess the on-going operational state of individual sensors within the system.*

NOTE 2 *Most sensors within a sensor system have an operational life of 1 to 3 years and will therefore require replacement with guidance from the manufacturer. Sensors near the end of their lifetime will generally be more susceptible to drift in their output before they fail. Sensors can also lose specificity/selectivity, sensitivity, response time and display more noise and an increased dependence on influence variables.*

Any reported faults and maintenance performed should be recorded for use in later quality assurance activities undertaken when publishing the final data set. A log of individual sensor replacements and serial numbers should be made.

4.4 Quality assurance

*COMMENTARY ON **4.4***

All instrumentation making air quality measurements, including the established reference quality instruments, suffer from measurement artefacts. How these artefacts are controlled and mitigated is the role of quality assurance (QA). This clause discusses various measurement artefacts and parameters that need to be considered and provides recommendations for the user on how their effects can be reduced. Figure 6 provides an overview of common measurement artefacts, parameters for consideration and a guide to the increased level of QA required to control these issues.

4.4.1 General

The required level of quality assurance should be selected as follows depending on the monitoring requirements and the measurement artefacts that the selected sensor system displays:

a) Comparability (**4.4.2**) for all studies; and

b) Drift (**4.4.3**), Noise (**4.4.4**), and Influence variables (**4.4.5**) depending on the monitoring requirements.

NOTE 1 *For example, a multi-sensor system long-term study will need to address all of the areas highlighted in Figure 6, whilst a short-term study, such as the Stirlingshire Villages Project[2)], might not need to address noise, sensor drift and influence variables as these effects are likely to be negligible.*

Procedures should be fully documented.

NOTE 2 *Documentation of procedures is essential so that the user can show how monitoring has been performed and quality assured. This is important for the defence of the results to other bodies such as auditors and challenges to the validity of the results.*

NOTE 3 *Although low-cost sensor systems can be used to measure indoor air quality, they are not suitable for occupational exposure testing due to uncertainty constraints, and the prevalence of potential interfering species that could invalidate the measurement. Particulate matter composition and size distribution might also be different in indoor air to outdoor air, e.g. differences in emission sources. To assess the performance of sensors indoors, they are compared to traceable measurements also made indoors in the same environment. Guidance on occupational exposure testing is available from the Health and Safety Executive's website[3)].*

NOTE 4 *Information on sensor technology and well-known performance issues is provided in Annex D.*

2) Available at https://www.environment.gov.scot/our-environment/air/stirlingshire-villages-project/.
3) Available at https://www.hse.gov.uk/health-surveillance/index.htm.

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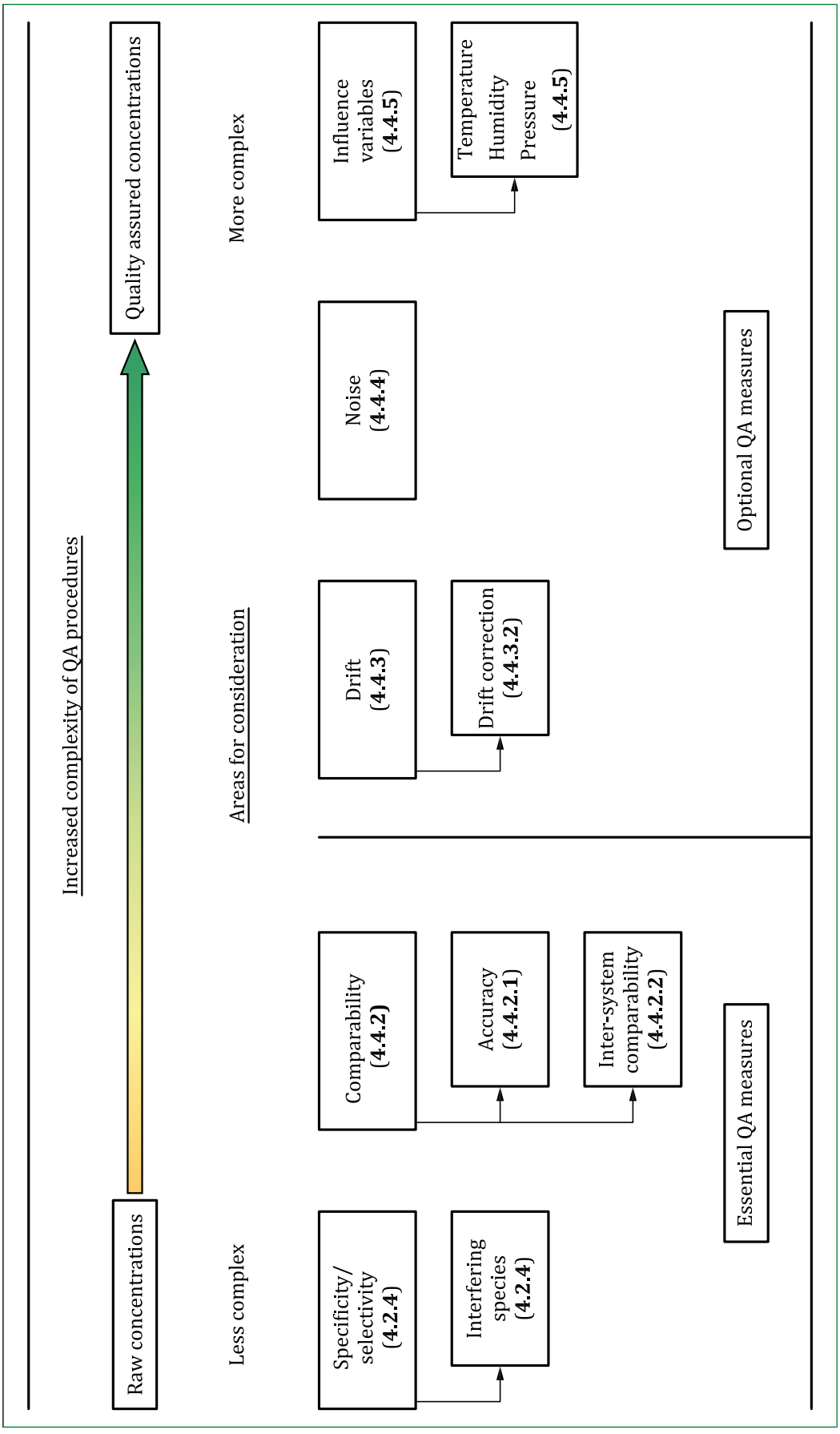


Figure 6 – Common measurement artefacts and areas for consideration

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4.4.2 Comparability

4.4.2.1 Accuracy

*COMMENTARY ON **4.4.2.1***

Not all calibrations by manufacturers/suppliers are performed in a pollution environment that is similar to where the real-world measurements will take place. It is therefore important that users perform co-location calibrations where possible, and these are outlined below. An example of how different sensor systems can perform straight out of the box is described in the case study in Annex C, C.1.

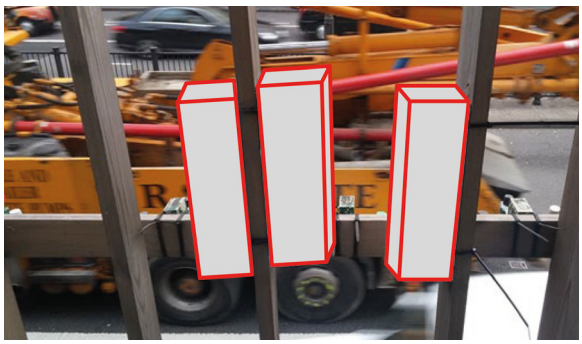
The sensor system should be co-located alongside a traceable reference quality instrument.

***NOTE 1** For example, those operated under Automatic Urban and Rural Network (AURN) or Local Air Quality Management (LAQM) quality assurance regimes.*

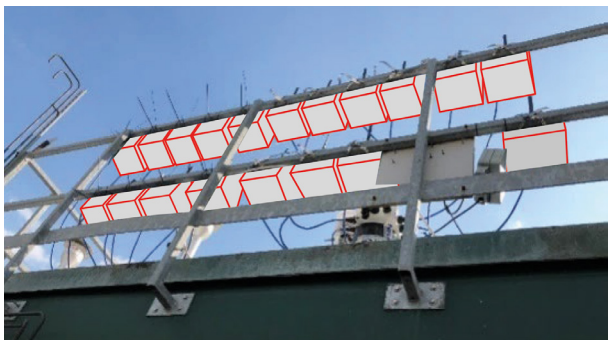
Co-location comparisons with traceable measurements should be made on a regular basis in line with the manufacturer's recommendations. The maximum time-period between such co-location comparisons should be annual, but shorter periods are preferable. Co-location comparisons should also be performed at a site classification (urban background/roadside etc.) similar to the future location of the sensor system.

***NOTE 2** Figure 7 provides two examples of co-location calibrations at National Network sites.*

Figure 7 – Example of co-location calibration studies where low-cost sensor systems are monitoring alongside reference instruments at AQ monitoring stations



a) Co-location study at AURN monitoring station in central London



b) Co-location study at AURN monitoring station in south-west London

Co-location calibrations should be performed for a period that is adequate to obtain an acceptable long-duration dataset for comparison. After the manufacturer's stated stabilization time,14 days should be the minimum co-location period, with longer periods being preferred.

As sensor system responses can be influenced by ambient temperature and humidity, co-location calibrations should be repeated in different seasons throughout the year. Sensor system responses to pollutants should be stable over time, i.e. have low drift rates, for the co-location calibration to remain valid.

***NOTE 3** Failure to carry out robust calibrations will mean that the co-location calibration is not transferable to the stand-alone monitoring location.*

***NOTE 4** An example of using co-location calibrations is described in the case study in Annex C. Co-location calibrations and the data analysis required are also described in PD CEN/TS 17660-1.*

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In a multiple sensor network configuration, a subset of sensor systems should be permanently co-located at reference stations to provide on-going calibrations. These calibrations should then be applied to the other sensor systems across the sensor network. For this calibration methodology to be valid, each individual sensor system should perform in a comparable manner to the other systems and have a response to pollutants that is stable over time.

NOTE 5 *In this way, a whole network calibration response can be applied to each sensor location. As well as manually determining and applying the network calibration, this can be performed in an automated manner, for example, using pre-training/machine learning/artificial intelligence style algorithms. These automated "whole network" methodologies are not yet well established and are continually being improved. Three examples of network calibration methodologies are given in Annex B and the limitations of machine learning are discussed in Note 6.*

NOTE 6 *Machine learning (ML) and artificial intelligence (AI) are advanced statistical analysis methods. When using ML or AI to predict pollutant concentrations from low-cost sensors, it is important to understand the underlying algorithms that are used and the conditions under which models were trained in order to properly assess the risk and uncertainty of the model. Whether using a simple ordinary least squares regression model, multiple linear regression or a more advanced ML approach, the model's ability to predict new values is likely to be biased by the range and quality of the data used to train the model. With air quality sensors, the training set might be biased if it is trained using co-located data from a single season, geographical location, and/or environment. If not properly accommodated, this training set bias can lead to inaccurate ML or AI predictions. If the data is overfitted or if the range of the data set is limited, then data quality will degrade during other seasons or if the sensor system is moved to another location or type of site (background/ roadside/rural etc.).*

All calibration methodologies that are used should be well documented by the sensor supplier, as well as the user, and be transparent to external assessment.

The following parameters should be taken into account when co-locating sensor systems with reference measurements:

a) maximum horizontal separation of sensor system to reference inlet and where possible equidistant from the pollution source (traffic) with allowable horizontal separation parallel to the road:

   1) ≤10 m for urban background;

   2) ≤5 m for roadside; and

   3) ≤1 m for kerbside;

b) maximum vertical separation of sensor system to reference inlet of ≤1 m; and

c) unrestricted air flow around sensor system and reference inlet.

NOTE 7 *If calibration is not possible, then the measurements might not be accurate, but they can still provide an indication of changes in concentration over time if the measurement response is stable over time.*

Internal algorithms programmed into sensor system hardware or external algorithms on data servers or subsequent data processing should be controlled. Changes to these algorithms can lead to changes in the "as measured" concentrations reported by the sensor, even if the actual ambient concentrations have not changed, therefore, instrument data traceability should be reviewed so that the data is not subject to changes in the processing algorithm or variable changes over the duration of the project. All information should be auditable if not already clearly visible in the data file.

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NOTE 8 *There are two main approaches to processing raw sensor output into usable and informative results:*

- *a machine learning approach which develops and evolves based on the environment it is exposed to during the training phase or period (external algorithm); or*
- *a fixed, version-controlled algorithm that remains unchanged for the duration of the product life which can be open to the user or (as in most cases) a "black box" approach (internal algorithm).*

NOTE 9 *When a sensor has exceeded its lifetime and needs to be replaced, care is needed to record if the design of the replacement sensor has changed, which might necessitate the use of an updated algorithm. Sensor serial numbers and algorithm version control is therefore essential to ensure that long-term measurements are robust.*

Calibration protocols should be fully documented for future reference, including for the purpose of an independent audit.

4.4.2.2 Inter-system comparability

COMMENTARY ON ***4.4.2.2***

Inter-system comparability is defined as how well sensor systems of the same type, measuring the same pollutant, compare with each other both in the short and long term. In many applications, comparing data from sensors across a geographical area is key to understanding how pollution varies, travels or evolves in order to identify "hot spots", which require some mitigation measures in order to reduce pollution. This is only possible if every sensor performs in a similar manner in the same network.

Where possible, all of the sensor systems should be co-located in a single location prior to deployment so that each system is exposed to well mixed air volumes for a period of time such that their performance is sufficiently similar. This co-location should be of the same site classification as any subsequent deployment for measurement campaigns.

NOTE 1 *This can be carried out in batches for large numbers of sensors sequentially if it is not possible to accommodate all of the sensor systems into a specific space.*

There should be an overlap of at least one sensor system from each batch into the next to aid comparison. This comparability co-location should be performed adjacent to a reference quality analyser to provide additional information and to meet the recommendations described in **4.4.2.1**.

NOTE 2 *If sensor systems have been shown to be comparable to each other, then the calibration obtained in* ***4.4.1*** *can be applied to other sensors within a network of sensors.*

Inter-system comparability protocols should be fully documented for future reference, including for the purposes of independent audit.

4.4.3 Drift

4.4.3.1 General

Drift should be monitored and corrected for if it becomes significant. To avoid short-term drifts, which are mostly caused when a sensor system is firstly installed at a location or if the system is relocated, the recommendations on acclimatization in **4.3.1** should be followed.

NOTE *Any observed drift will be a combination of zero and sensitivity drift. These can be assessed by performing co-location calibrations at measurement sites; in the rest of this clause this combined drift is referred to as "sensor drift".*

Procedures for addressing drift should be fully documented for future reference. Uncorrected "as measured"/"raw" concentrations should be stored separately from the corrected concentrations.

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4.4.3.2 Drift correction

*COMMENTARY ON **4.4.3.2***

Recommendations for quality assurance to address drift are covered in this clause and assume such drift is linear in time. If the user is applying a pre-training/machine learning/artificial intelligence style algorithm, then this approach is not relevant.

A co-location calibration with the reference quality analyser should be performed at the beginning and end of the measurement campaign, or annually, whichever is shortest.

The drift in response to the sensor should be calculated from the difference between the two calibration factors obtained at the co-location calibrations, and then the drift should be corrected for if needed.

If a drift correction is required, the drift rate [D_{rate}] should first be calculated as follows (Equation 1):

$$D_{rate} = \frac{CF_{end} - CF_{start}}{t} \quad (1)$$

where:

CF_{end} is the calibration factor at end of period;

CF_{start} is calibration factor as start of period; and

t is time between the calibrations.

The drift rate should be calculated on a per hour/day/month basis, depending on the measurement period and magnitude of drift.

The drift in calibration factor should then be applied in a linear fashion over the period between co-location calibrations.

The "as measured"/"raw" measurements should then be corrected as follows (Equation 2):

$$Conc_{corrected} = Conc_{raw} \times \left[CF_{start} + \left(D_{rate} \times t_{elapsed} \right) \right] \quad (2)$$

where:

$Conc_{corrected}$ is the drift corrected concentration;

$Conc_{raw}$ is the as measured (raw) concentration; and

$t_{elapsed}$ is the time elapsed since the initial (start) calibration.

If sensor units have been shown to have comparable performance, then this drift correction should be applied to other sensors within a network of sensors.

4.4.4 Noise

Sensors should not be placed close to any sources emitting electromagnetic fields (EMF). Where this is not possible, electromagnetic interference shielding should be employed.

***NOTE 1** Measurement noise can be induced by variations in electronics and processing, and noise levels are known to vary with atmospheric conditions such as temperature and humidity. Noise levels have also been shown to increase in the presence of RF and EMF fields in close proximity to certain sensors. Electrical power stability can also increase the levels of noise or induce ghost spiking of sensor outputs. The use of ferrite cores in power cables and high-quality power converters can often mitigate these effects.*

***NOTE 2** Vibration might also increase noise levels in certain sensor types. Anti-vibration mounts can be incorporated in locations where this is expected to be severe.*

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NOTE 3 *Some sensors, depending on their design, are noisier than others. This noise can be described as "intrinsic noise".*

Measures implemented should be fully documented for future reference, including for the purposes of independent audit.

NOTE 4 *Many sensor systems are also able to make measurements on a shorter time base than reference methods, although this can come at a cost of reduced precision and increased noise. Reducing the measurement period of the reference methods might also increase the noise and decrease their precision.*

4.4.5 Influence variables

COMMENTARY ON ***4.4.5***

Sensor performance can be affected by changes in influence variables, such as temperature, humidity or atmospheric pressure, especially if these changes are rapid, i.e. from wind gusts, sudden changes in weather conditions or exposure to direct sunlight at certain times of the day. Optical particulate matter sensors can be influenced by high humidity and fog episodes, which lead to artificially elevated measured concentrations due to changes in particle size or water aerosols under such conditions.

Influence variables should be reduced by avoiding locations where the device is exposed to sudden temperature changes, sources of fog, steam, mist or humid air from vents and exhausts. If these locations cannot be avoided, then manufacturers should be consulted on options available to address these concerns, e.g. heated inlets or aerosol drying systems.

The likely effect of influence variables should be documented, and any mitigation strategies used recorded for future reference.

4.5 Data screening

All of the data should be screened after it has been through the documented quality assurance procedures to remove any erroneous measurements. Reasons for data deletion/redaction should be documented.

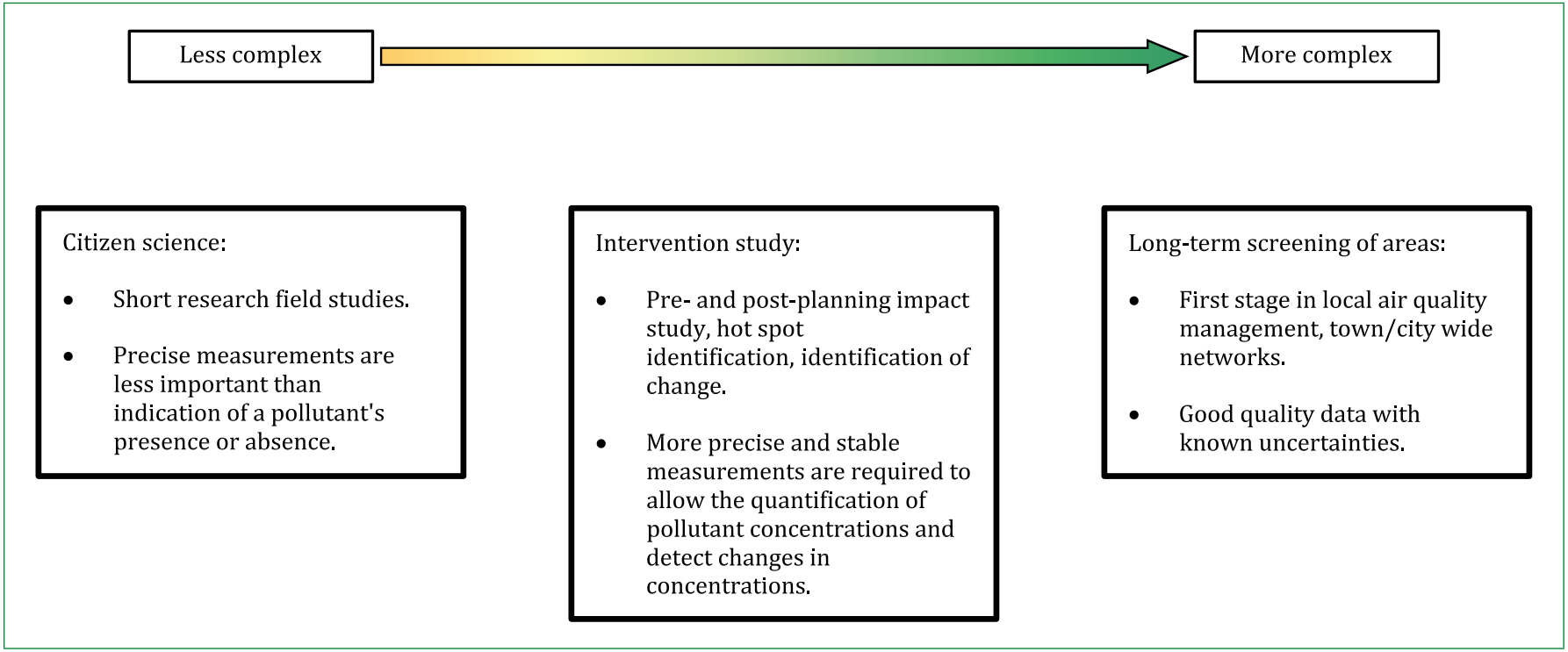
NOTE *Examples of erroneous data include:*

- *PM concentrations off scale during high humidity/fog events;*
- *carbon monoxide concentrations being consistently lower than the regional background of 100 µg/m^3;*
- *carbon dioxide concentrations being consistently lower than the regional background of ~420 µmol/mol;*
- *transient humidity due to passing traffic; and*
- *concentrations at or below the detection limit.*

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Annex A (informative)
Possible monitoring scenarios

Figure A.1 – Possible monitoring scenarios



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Annex B (informative)
Examples of network calibrations

*COMMENTARY ON **ANNEX B***

*This annex provides three examples of network calibration methodologies (see also **4.4.2.1**). Users of air quality sensor systems are likely to fall into two main categories, namely those who employ systems in small numbers (e.g. one to five systems) and those who are involved in studies, typically in cities, which may use a high-density network and may involve hundreds of systems. A recent research study [10] indicates that new remote cloud-based calibration techniques are being developed, which might transform air quality monitoring in the future for certain pollutants, including NO_2 and $PM_{2.5}$. As the procedures are in their infancy and are an emerging field, they warrant some additional explanation in this annex but it is for users to develop appropriate validated algorithms which can be applied.*

*The examples provided in this annex are produced with permission from the University of Cambridge (**B.1**), Imperial College London (**B.2**) and Environmental Instruments Ltd/Cheltenham Borough Council (**B.3**).*

B.1 Breathe London Pilot Study methodology

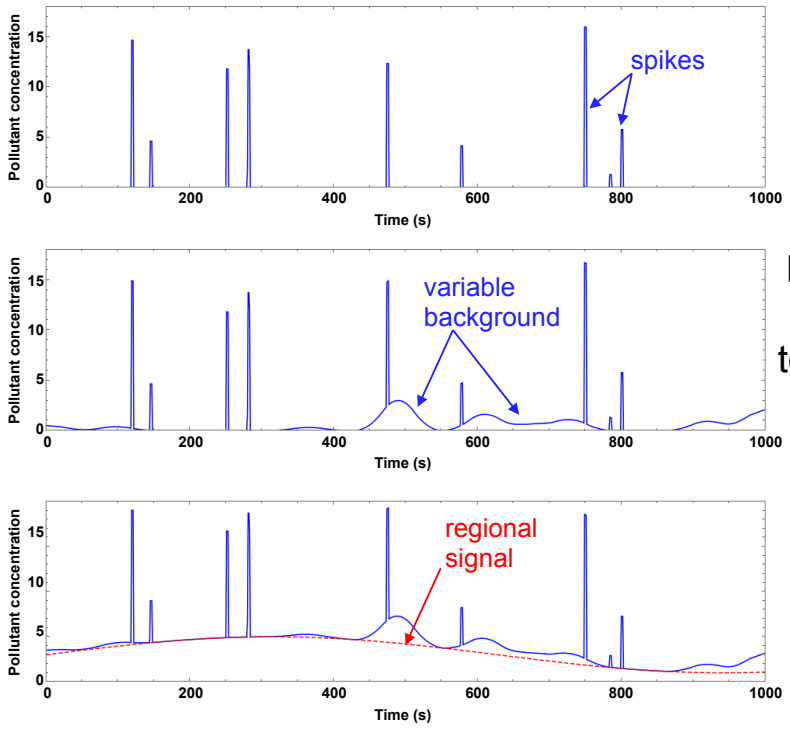
A remote network calibration method developed at the University of Cambridge and applied in the Breathe London pilot study [14] [15] explores the benefits of rapid sampling, making use of one-minute average readings obtained from a large network of air quality sensors.

The key element of the method is that the shorter timescale monitoring makes it possible to separate sources of pollution detected by the sensors into different categories for data processing. This is illustrated schematically in Figure B.1 for three types of sources (local, dispersed, and regional), which have different signatures.

The calibration methodology requires the extraction of the regional pollution signal from the local pollution signatures for all the sensing systems in a network. An important assumption inherent in the method is that under certain meteorological conditions the regional pollutant signal is approximately uniform across the entire network for long periods, but that it also varies in time.

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Figure B.1 – Separation of emission sources



For each pollutant, suitable regression analysis can then be used to establish the level of agreement between any pair of sensor systems in the network. One of the sensor systems is then calibrated and has traceability to a reference method, the other is termed the "candidate system". This comparison approach is then applied to the entire network of low-cost sensor systems to yield individual calibration parameters (gains and offsets) for each sensor.

Statistical analysis criteria which may be considered in the data analysis include a good correlation between the reference standard and candidate system (e.g. $R^2 > 0.7$), and that the root mean square error (RMSE) is sufficiently low in comparison to the average concentrations during the co-location study (e.g. normalized RMSE < 0.5). The output of this approach is a series of dedicated gain and offset values which are individually applied to the relevant air quality sensor in the network, which provides traceability to the reference method.

B.2 Breathe London ongoing methodology

Following the Breathe London pilot study methodology detailed in **B.1**, the successor network was deployed in Greater London, UK, from January 2021, and uses a unique continuous network scaling calibration approach based on the near real-time relationship between sensor and reference measurements to reduce sensor measurement uncertainty. The network (see Figure B.2) is operated by Imperial College London[4)] and currently consists of over 420 locations monitoring the regulated pollutants NO_2 and $PM_{2.5}$. Key performance indicators (KPIs) for the project are summarized in Table B.1 and include expansion from the original 136 sites at a rate of 5% per year through node purchase by groups or individuals.

4) Information available at https://www.breathelondon.org/.

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Figure B.2 – Evolution of the Breathe London monitoring network

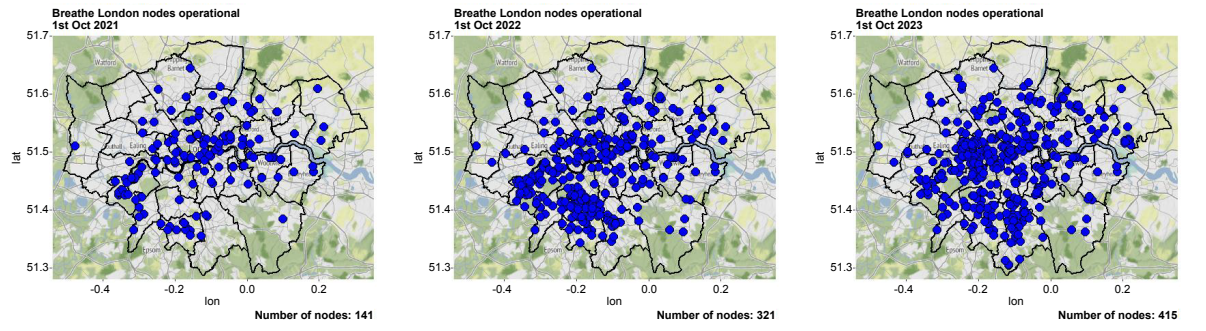


Table B.1 – Summary of Breathe London key performance indicators with outline aims associated with each KPI

KPI	Aim
COVERAGE Install, maintain and insure air quality sensors at 100+ sites	Ensure sufficient density of coverage to be a meaningful lower capital cost sensor (LCCS) network
QUALITY Demonstrate output data continues to meet uncertainty requirements	Make sure data is of an appropriate quality and provides functionally useful data
HEALTH Ensure a minimum 90% of sensors are in operation at any given time	Ensure network nodes remain functional with minimal downtime so as to be a reliable network
EXPANSION Increase the number of sensors in the network by an additional 5% per year	Commit to community and wider buy-in based on proven value to users
COMMUNICATION Website is live continuously and displays data in real time Data is also available via an Application Programming Interface (API)	Ensure open data and ease of access

The goal is to meet the uncertainty requirements of the EU Air Quality Directive [3] for indicative (Class 1) methods for particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) through the application of a two-stage calibration and correction procedure.

Stage 1 employs a primary co-location of the sensor systems with reference instruments at Honor Oak Park London Supersite (urban background site). Functionality checks are carried out and, if passed, first order correction parameters unique to each sensor node are then determined to address deviations in performance between individual nodes. As with similar pre-deployment co-location exercises, the initial co-location period is statistically highly unlikely to be fully representative of the full range of climatological and pollutant regimes that an installed node is likely to encounter over typical deployments lasting months to years at sites ranging from kerbside to suburban background.

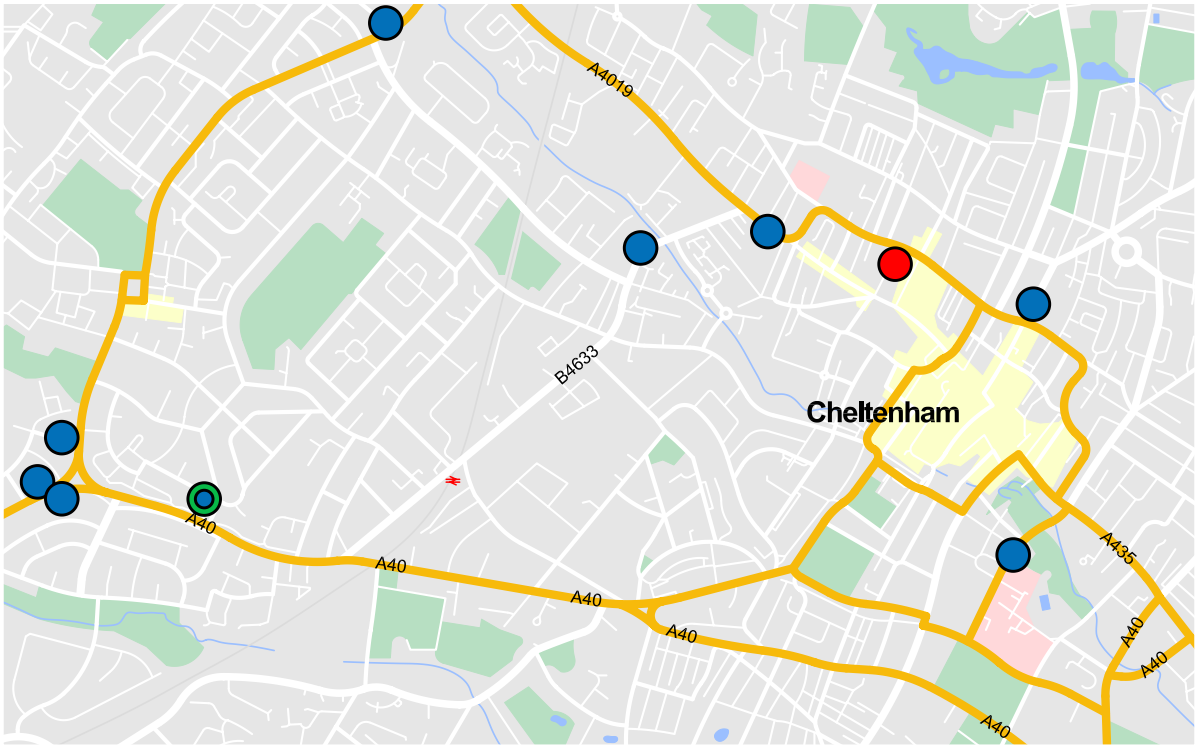
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Stage 2 uses a cohort of 19 highly characterized sensor nodes (referred to as Tier 2 nodes) which are dispersed and permanently co-located at London Air Quality Network (LAQN) reference stations across the Breathe London domain. Tier 2 nodes are routinely corrected using a system where hourly data are compared at each of these paired sites to generate daily multivariate correction factors derived from reference measurements of cross interfering pollutants and meteorological parameters. This dynamic method is designed to correct for deviations between the sensor and reference measurements as well as impacts from changes in meteorology. It is the basis of the Breathe London dynamic network correction algorithm as used for the standard Breathe London nodes.

B.3 Methodology deployed for Cheltenham Borough Council Study

A small-scale implementation of a network calibration method, termed "long distance scaling" (LDS) was carried out by Environmental Instruments Ltd on behalf of Cheltenham Borough Council. The study focused on making ambient measurements of NO_2 with a network consisting of nine low-cost sensor systems deployed in Cheltenham, which covered different location types, including urban traffic and urban background sites. In addition, there were two calibrated reference quality and well maintained chemiluminescence analysers measuring NO_2. One reference analyser was selected as the network's route for calibration traceability, while the second was used as the control comparison and was co-located with one of the sensor systems. Figure B.3 provides a map of the sensor network and the reference instruments deployed in Cheltenham.

Figure B.3 – Sensor-system network deployment in Cheltenham



Key

1 BLUE: Sensor system locations

2 RED: Calibrated control reference instrument

3 GREEN: Traceable reference calibration instrument

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The time resolution of the NO_2 measurements did not fully exploit the rapid sampling that is possible with low-cost sensors. Instead, the data consisted of 15-minute averages for both the sensor systems and reference instruments, which was sufficient for the LDS calibration method to be applied and avoided premium charges for one minute resolution data. The team implemented a proprietary method to separate local and regional sources of pollution. Two test approaches, T1 to T2, are presented in Table B.2, which have employed orthogonal regression and equivalence testing methods.

NOTE *More information on these testing methods is available in BS EN 16450 and Guide to the demonstration of equivalence of ambient air monitoring methods [16].*

Table B.2 – Demonstration of LDS calibration method

Comparison	Test [A)]	Pre-scaled (T1) [B)]	Scaled (LDS) (T2)[C)]	Target
Linearity	R2	0.85	0.85	> 0.8
Bias	Slope	1.21	0.98	0.78 ≤ 1 ≥ 1.29
	Offset	-3.03	2.97	-5.1 ≤ 0 ≥ +5.1
Accuracy	RMSE (nmol/mol)	4.27	4.21	< 5
Confidence	% Uncertainty	58.8%	18.7%	< 25%
Completeness	Data capture %	100.0%	100.0%	> 90%

A) All tests completed using the same period of data.

B) The "out of box" performance (pre-scaled) from the co-located instrument compared against the control monitor. This data highlights the necessity to carry out re-calibration from factory settings.

C) The performance following the application of the "network calibration" (Scaled-LDS) method. In this case, scaling factors were determined for all nine sensor systems by comparison with the reference monitor. The data showed improved agreement between the sensor system co-located with the control monitor. Results from co-located NO_2 diffusion tubes and the sensor systems in the network also confirmed the validity of the LDS calibration method for cases where there was no reference instrument.

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Annex C (informative)
Case studies on improving the comparability of sensor systems

*COMMENTARY ON **ANNEX C***

The following two case studies are produced with permission from the Wolfson Atmospheric Chemistry Laboratory, Department of Chemistry, University of York, UK. They provide information on performance issues with sensor systems and how these issues can be addressed, and performance improved.

*The first case study shows the importance of inter-system comparability (see **4.4.2.2**) and the second case study shows how the accuracy with a reference scale (see **4.4.2.1)** can be accomplished through co-colocation calibrations.*

C.1 The importance of inter-device comparability

This case study discusses the issue of "out of the box calibrations" not being fit for purpose and demonstrates how individual sensor calibrations can improve inter-device consistency.

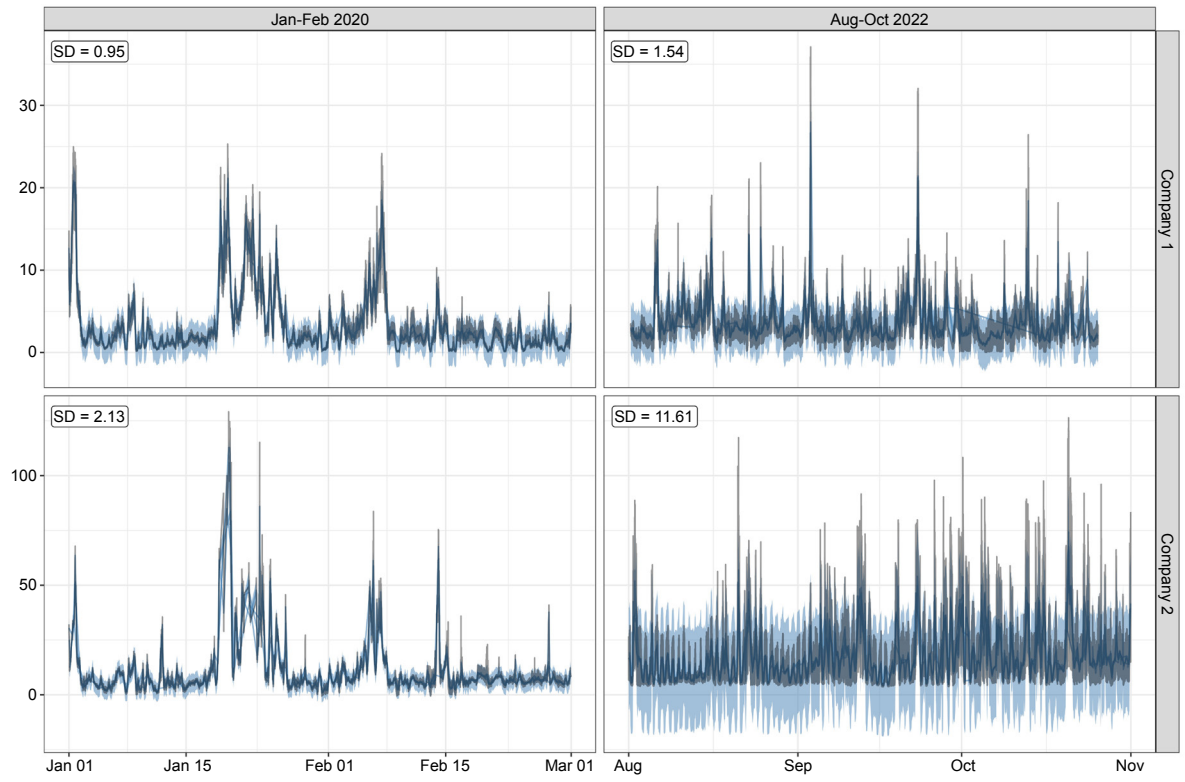
Case study 1: Low-cost air pollution sensors and the importance of inter-device comparability

A major strength of low-cost air pollution sensors is the ability to create dense networks of devices that can provide information on pollutant spatial distributions, which is not obtainable from traditional sparse reference measurement networks. Designing and interpreting the data from networks is a non-trivial task, especially when thinking about how to calibrate a network and account for measurement uncertainty in the data interpretation. A potentially important feature to be considered when selecting devices for a network is inter-device consistency or comparability, i.e. how similar "identical" devices respond across the network. This is particularly important, as the relatively small size and power consumption of low-cost sensor devices means they can make measurements in locations inaccessible to reference devices, which makes co-location calibrations of every device difficult or impossible in their final measurement location. If devices show high inter-device comparability, however, users of the data can be more confident when interpreting observed differences across the network that these are genuine differences and not simply due to chance. How inter-device comparability evolves with time is also important to know, particularly if the desired use case involves long-term deployment.

As part of the UK QUANT study, multiple "identical" devices were co-located for the first 2 months and the final 3 months of the 3-year QUANT deployment in order to assess inter-device comparability, and how this can change over time. Figure C.1 shows the inter-device comparability of two companies' $PM_{2.5}$ measurements during the first 2 months (left) and the final 3 months (right) of the 3-year QUANT deployment. The reported standard deviation (SD) values correspond to the "comparability," a measure of inter-device variability with a lower value indicating higher inter-device comparability. Company 1 (top) has a greater inter-device comparability than company 2 over both of the observed time periods and also exhibits less of a reduction in inter-device comparability between the two time periods, with an approximate doubling of the comparability metric for device 1 compared with an increase of a factor of 5 for company 2.

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Figure C.1 – Inter-device comparability



NOTE *Inter-device comparability of $PM_{2.5}$ measurements from "identical" devices from two companies. Each company has measurements from at least three devices (faded grey lines), with the solid blue line showing their timewise mean. The labelled SD is the comparability, defined as the standard deviation of every measurement's distance from its mean. The shaded blue region encompasses two SDs from the mean.*

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C.2 Benefits of co-location calibrations

This case study discusses the benefits of co-location calibrations with traceable methods to remove measurement artefacts and provide robust calibrations that are suitable for local conditions/ different site types. It shows how co-location calibrations can significantly improve low-cost sensor performance. However, it is important that calibration performance is evaluated thoroughly, as issues such as over fitting or new bias introductions can reduce the benefits of co-location calibration or potentially worsen performance.

Case study 2: Low-cost air pollution sensors and co-location calibrations

All instruments used to measure air pollutants require some form of calibration to convert raw electrical signals into measures of concentration or mixing ratio in their standard units. For many reference instruments, this typically involves sampling a certified gas standard of a known concentration and identifying the parameters for a linear correction. This approach assumes there are no other factors that impact on the sensor reading except from the target pollutant. Unfortunately, this is not the case with many low-cost sensor technologies, which are frequently sensitive to other atmospheric constituents, such as water. As such, co-location with well characterized reference instruments is recommended as the preferred calibration approach, where correction functions are developed to maximize the agreement between the sensor and the reference instrument.

These functions can take the form of simply applying a slope or offset, or can involve more complex nonlinear forms, potentially incorporating external data sources such as temperature or humidity. These correction routines can also be automatically identified from the data using machine learning algorithms. Commercial low-cost air pollution sensors all use some form of universal calibration to provide "out-of-box" measurements. In order to achieve optimal performance, it is recommended to tailor the calibration to the deployment environment by performing a new co-location study in a representative setting.

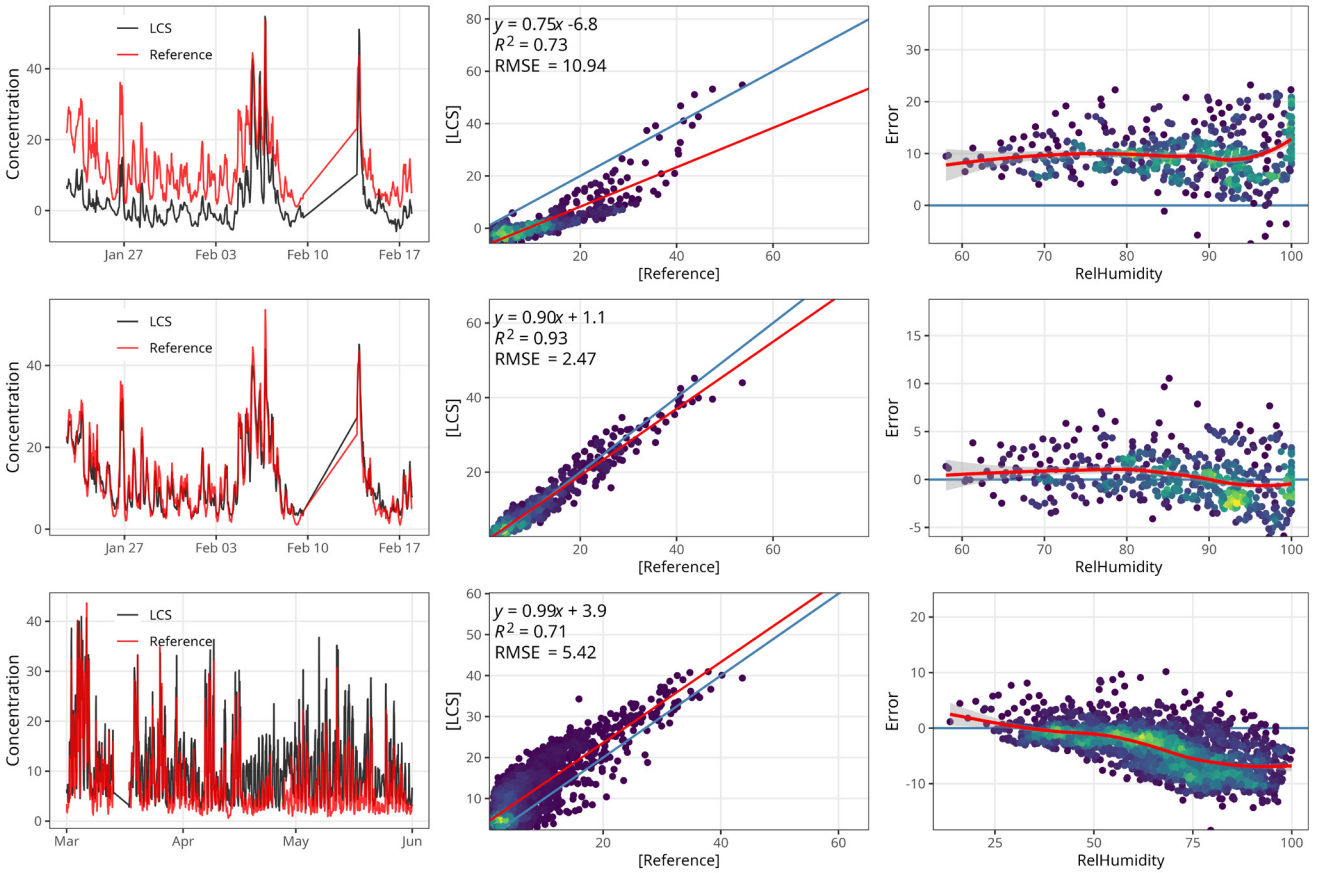
As part of the UK QUANT study, a set of commercial low-cost sensor devices were co-located with reference grade instruments at several urban locations. After running from December 2019 to April 2020 in the out-of-box configuration, reference data from the start of the study until 18 February 2020 was provided to the manufacturers with the intention for them to retune their calibrations. An example of the improvements seen following this co-location calibration can be seen in Figure C.2, which shows data from a low-cost NO_2 sensor compared with co-located reference measurements under different calibration algorithms and two time-periods.

The out-of-box measurements from 22 January 2020 until 18 February 2020 (upper panel) show a clear under prediction by the low-cost sensor, and what seems to be a humidity dependence in the measurement error at high humidity. Following the application of a calibration model using reference data from this same period (middle panel), the new measurements are much improved in terms of their accuracy (quantified by RMSE), their linearity (quantified by R^2), and also removing the apparent humidity dependence in the error.

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Figure C.2 – Data from a low-cost NO_2 sensor compared with co-located reference measurements under different calibration algorithms and two time-periods



NOTE 1 *Plots showing the impact of co-location calibration on the agreement between a low-cost NO_2 sensor and a reference NO_2 measurement at an urban background site in Manchester. The top row of plots shows the reference and "out-of-box" sensor data between 22 January and 18 February 2020 as a timeseries (left), regression plot (middle) and plot of the difference between the two as a function of humidity (right).*

NOTE 2 *The data in the top plots were then used to perform a co-location calibration, which when applied over the same time period resulted in a significant improvement in agreement (middle row plots). The increased agreement between the sensor and the reference instrument achieved by the co-location calibration is seen to degrade somewhat outside of the training data period, with the bottom row of plots showing co-location calibrated sensor and reference data for 1 March 2020 to 1 June 2020.*

Annex D (informative)
Sensor technologies and performance issues

D.1 Sensor technologies

D.1.1 Overview

Sensor systems can be classified under two categories:

a) self-contained; and

NOTE 1 *Self-contained systems are able to make all the measurements required, internal to the sensor system, to determine the measured concentration. These measurements can be used to make corrections for cross-interferents or the effects of influence variables such as temperature and/or relative humidity.*

b) those that require the use of external measurements not provided by the sensor unit.

NOTE 2 *Some sensor systems are reliant on additional external measurements outside of the sensor system itself to make corrections for cross-interferents or the effects of influence variables such as temperature and humidity. In this scenario, and without revealing proprietary details of algorithms, the manufacturer confirms whether external measurements (e.g. reference data, other sensor data or metadata) are being interrogated to deliver results to the user, and the status of the external data is traceable and verified through the quality assurance regime.*

The following are also common technologies employed in low-cost air quality sensor systems:

1) electrochemical (**D.1.3**);
2) non-dispersive infrared (**D.1.4**); and
3) optical light scattering techniques (**D.1.5**).

It is important that the performance of the whole sensor system is understood to ensure that the chosen solution is suitable for the task.

D.1.2 Metadata

Metadata provides additional information to support the results produced by the sensor system networks as follows:

a) quality information, which includes a form of data flagging system indicating faults or sensor health, with access to calibration and any ongoing audit data;

b) information about the individual sensors and sensor type, including details of the measured quantity with either links to the actual data for performance or validation data for the sensor type;

NOTE *Examples include history (age), serial model/number, measurement units, calibration history, geographical location, calibration factors and re-zeroing.*

c) ancillary data, which includes additional data sets required to analyse or correct sensor readings, for example, environmental data covering temperature/pressure or the values of interfering quantities (e.g. water vapour/relative humidity), or data which can help in the interpretation of the results (e.g. wind direction and speed). Meteorological measurements are classified in accordance with their sources such as:

   1) from a sensor system (with reference to standards covering the data);
   2) measurements obtained from the UK Meteorological Office or other independent data providers;

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3) modelled meteorology; and
4) other parameters used for data processing and their sources;

d) information on the measurement/network configuration, which includes:

1) time of the measurement;
2) species measured (raw or processed data);
3) whether the data is from a single sensor system/site or a network of sites;
4) site information – for example precise sampling location, sampling system and sampling point details (height, flow rate etc); and
5) version control for open access data processing algorithms, proprietary algorithms (with a declaration of use of other publicly funded data, e.g. AURN), and hybrid open access and proprietary algorithms.

D.1.3 Electrochemical sensor

An electrochemical sensor consists of a diffusion barrier, a sensing (working) electrode, a counter-electrode and a reference electrode, separated by a thin layer of electrolyte. When a voltage is applied between the sensing electrode and a reference electrode, gas diffuses into the sensor through the barrier and is catalytically oxidized or reduced at the surface of the working electrode. The magnitude of the current is controlled by how much of the target gas is oxidized/reduced at the working electrode. Sensors are designed so that the gas supply to the electrolyte is limited by diffusion and thus the output from the sensor is linearly proportional to the gas concentration.

NOTE *Oxidation is normally used to detect CO, SO_2, NO, NH_3, and H_2S, whilst reduction is normally used to detect NO_2 and O_3.*

Diffusion control offers another advantage. Adding a diffusion barrier allows the sensor to target a particular gas concentration range. In addition, since the diffusion barrier is primarily mechanical, the calibration of electrochemical sensors tends to be more stable over time and so electrochemical sensor-based systems in diffusion mode avoid flow rate sensitivity drift problems. Although the mechanically defined diffusion rate sets the ideal sensitivity, sensitivity is also controlled by the catalytic reaction rate. Sensitivity can be less than diffusion calculated due to low temperatures, shift of the reference electrode potential, long-term loss of catalyst activity or inadequate quantity of catalyst. Sensitivity is checked at regular intervals as defined by the manufacturer.

Zero (baseline current) can either increase or decrease reversibly, mostly driven by the average relative humidity (RH), so will show seasonal drift which needs correcting by quality assurance procedures. Baseline current is also temperature dependent. Sensitivity will decrease during the lifetime of the sensor, with different sensor types from different manufacturers showing different rates of loss of sensitivity.

When the sensor system is initially deployed or moved to a new type of location, electrochemical cells require typically 5 to 10 days to fully stabilize.

Electrochemical sensors can suffer from interference from gases other than the gas of interest. This interference can be reduced by placing a filter in front of the diffusion membrane or applying a bias voltage to the working electrode, e.g. ozone can cross interfere with nitrogen dioxide electrochemical sensors.

Oxygen is an essential ingredient in the reaction with the target gas to be measured and in maintaining the generated current when gas is present. If the oxygen supply is inadequate, the sensor does not operate properly, and cannot be used for certain applications. This is unlikely to be a factor when making ambient air quality measurements but is a factor if nitrogen balanced calibration gases are applied for a longer period than 30 min.

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The response of an electrochemical cell is dependent on temperature, so it is essential to have good temperature control/compensation within the sensing system deployed. If this is not the case, then the sensor's performance will change with temperature and any calibrations will be invalid.

Dry atmospheres can inhibit the performance of electrochemical sensors and thus make them unsuitable for monitoring of ambient air with very low relative humidity, i.e. below 20% RH at 20 °C.

D.1.4 Non-dispersive infrared (NDIR) sensor

The main components of a NDIR sensor are an infrared source (lamp), a sample chamber, a light filter and an infrared detector. The IR light is directed through the sample chamber to the detector. The gas in the sample chamber causes absorption of specific wavelengths according to the Beer–Lambert law, and the attenuation of these wavelengths is measured by the detector to determine the gas concentration. The detector has an optical filter in front of it that eliminates all light except the wavelength that the selected gas molecules can absorb. This design has been updated in recent times to replace the broadband tungsten lamp source with a LED tuned to give a narrow band of IR radiation spanning the gas of interest's absorption features and the reference channel wavelength. Almost all NDIR sensors of both broad band and narrow band type have a reference channel to compensate for source intensity drift.

LED light sources, twinned with photovoltaic detectors reduce the power requirement for NDIR sensors from typically 100 mW to 300 mW to 0.5 mW to 10 mW, drastically improving battery life and reducing warm up time due to the greatly reduced generated heat. However, they are more susceptible to condensation at high humidities because they do not self-heat, unlike hot black body tungsten lamp sources.

D.1.5 Particulate matter sensors

Most particulate matter sensors incorporated in sensor systems are optically based and make measurements using light scattering and particle sizing. These sensors generally count the number of particles and based on their estimated size, use an assumed density and refractive index to calculate an equivalent mass of the detected particles.

Any assumed size distributions made by the sensor may not be the same as the actual ambient aerosol size distribution. This can be especially important at roadside sites, sites close to industrial emissions and locations close to building sites.

Optical particle sensors can suffer cross interference from water vapour concentrations close to the air saturation point, which results in fogging of the sensor optics or water droplets being detected as airborne particulate matter. Heating of the sensor inlet can reduce this cross interference, but care needs to be taken not to overheat which may lead to the loss of volatile components from the particulate matter being measured.

At humidities above 60% RH, particles will swell, increasing their apparent size and giving high readings. Some particle monitors include inlet heaters to reduce this problem. Alternatively, some manufacturers apply a correction algorithm dynamically (within the device) in order to correct for this error.

Any drift in flow rate or pressure drop dependency can increase the measurement uncertainty.

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D.2 Performance issues

D.2.1 Overview

Due to the nature of sensor systems, they are prone to effects from influence variables such as water vapour, ambient temperature and can exhibit different measurement artefacts. To minimize these issues, sensor systems undergo formal type testing evaluations. If this is not possible, the user can attempt to understand possible issues by consulting supplier information or published literature.

The following list highlights possible measurement issues:

a) power supply problems associated with EMF and RF interference (**D.2.2**);

b) fog effects with particulate matter (PM) data (**D.2.3**);

c) anomalous NO_2 concentrations (**D.2.4**); and

d) aerosol size distribution for PM sensors (**D.2.5**).

D.2.2 Power supply problems associated with electromagnetic field and radio frequency interference

At certain locations, PM sensor outputs might be subject to regular or irregular spikes due to EMF interference during data transmission. Some effects on gas sensor data are also observed as offsets in the measurements.

Pumps for gas sampling and fans in PM sensors can also cause interference, especially with electrochemical sensors.

External sources, especially smart phones and two-way radios, generate significant EMF and the entire instrument needs to be shielded to protect from electromagnetic compatibility (EMC)/electromotive force (EMF) spikes on the sensor signal, especially the electrochemical sensors.

The selection of appropriate power supplies by the manufacturer may provide a remedy.

D.2.3 Fog effects with PM data

During episodes of fog, optical particle counters (OPCs), which do not have heated inlets (in order to save power), may be unable to differentiate small water droplets from particles. High humidity data flags can be used to identify such fog events, which are not very common, and only affect the data for relatively short periods.

D.2.4 Anomalous NO_2 concentrations

Some NO_2 electrochemical sensors incorporate a filter to remove ambient ozone, which can act as a cross interferent. In areas where ozone concentrations are high the filter will lose filter capacity over several months to years, depending on the ozone concentration. In high traffic areas, where there is little ozone present, the filter takes longer to be affected. Degradation of the ozone filter can lead to an over estimation of nitrogen dioxide concentrations. Periodic co-location studies with a chemiluminescence reference instrument can assist in identifying this problem.

D.2.5 Size dependency in PM sensors

Some PM sensors based on optical techniques report $PM_{2.5}$ and then employ specialized algorithms which assume a certain particle distribution to report PM_{10}. It is important that such sensors have been evaluated under conditions where there is $PM_{coarse} = (PM_{10}\text{-}PM_{2.5})$ present to ensure that the estimation of PM_{10} is correct. Unless this condition is met then the reliability of PM_{10} measurements may be questionable.

Users are encouraged to co-locate and calibrate PM sensors against the reference method. It is well known that reference equivalent methods may deliver different calibration factors based on measurement location and environment. Care is required in interpreting measurements carried out at industrial sites where the particles and their distributions are different from those normally present in air quality monitoring applications.

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