OPENAIR

Operational Network of
Air quality Impact Resources

Best Practice Guide

BP405 | Manage and analyse

Data interpretation: correction and harmonisation

Introduction

To support activities that create impact, raw sensor data must be interpreted through a process that begins with data correction and harmonisation. Data correction compensates for various biases and interference factors found in raw data, through calibration and the application of various correction factors. Harmonisation ensures that corrected data is then stored and presented in a usable and readable format that aligns with standards, guidelines and an internal project data ontology.

Data correction and harmonisation requires an understanding of data quality concepts (e.g. accuracy, precision, bias, drift, noise), calibration methodology, data ontology, and averaging periods. This chapter presents practical advice relating to the main processes for correcting and harmonising data produced by low-cost air quality sensors. These include:

- **calibration corrections** (calibration correction for all devices of one type; calibration drift correction, where correction is adjusted over time to account for sensor degradation; corrections for inter-device measurement variability; calibration for different types of particulate pollution)
- **environmental interference corrections** (correcting for common forms of environmental interference, such as temperature and humidity)
- **data harmonisation** (converting data expressed in different formats into a single, harmonised format, as defined by a data schema).

Who is this resource for?

This resource is for local governments and other organisations undertaking similar projects. It is intended for staff engaged with the design and delivery of air quality monitoring projects, including project managers, environmental officers, smart city leads, and planners. It is also a useful reference for senior management who wish to understand the complexities and challenges related to this kind of project.

How to use this resource

This OPENAIR Best Practice Guide chapter provides a high-level guide to data correction and harmonisation. It is the second in a series of four chapters on the topic of data interpretation. It is recommended you read the overview chapter first, and then refer to the other chapters on data interpretation (quality control and analytics) in the order outlined in Figure 1.

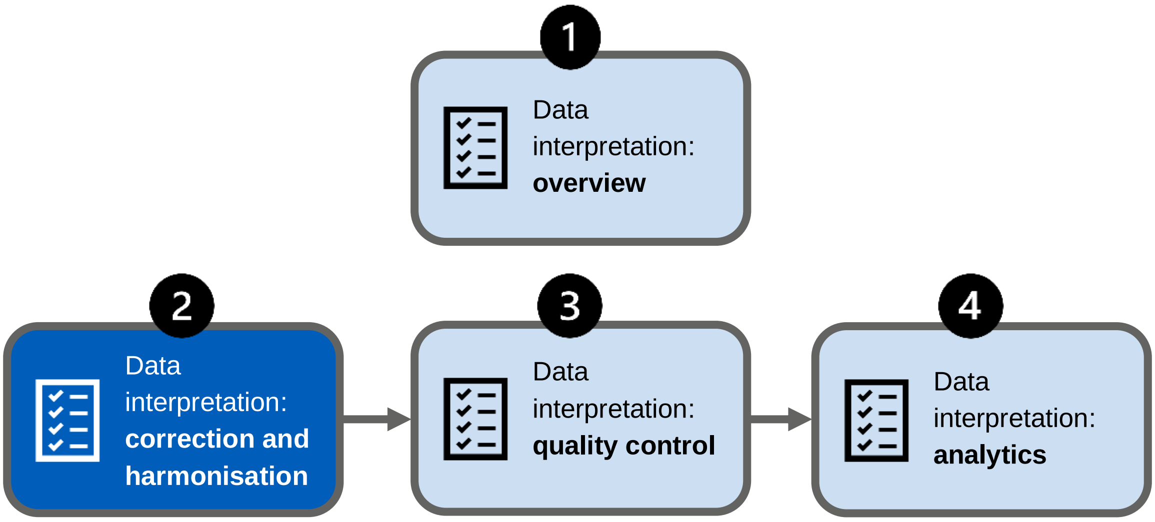

Figure 1. OPENAIR data interpretation Best Practice Guide chapters

Key messages

The key messages of this chapter are:

- Data correction and harmonisation can involve a range of approaches, of varying complexity. While it is always necessary to some degree, the specifics of your data use case will dictate your requirements in terms of effort, resources, and expertise.
- Data correction and harmonisation can be applied manually (to exported static data sets), or built into the functionality of an IoT or data platform with varying degrees of sophistication. It is a good idea to consider your data correction and harmonisation requirements as part of your technology procurement decision-making process.

TIP: Tools for data correction and harmonisation
Correction and harmonisation of your data can be done manually or automatically.

A) Manually
By using spreadsheets (e.g. Excel), or by accessing a range of online data interpretation resources.

B) Automatically
By implementing data correction and harmonisation automatically, either:
1. at the device level, as part of device firmware
2. in your IoT or data platforms.

For live streaming of data, an automatic approach is recommended. Speak with your device and platform vendors about the functionalities they can support.

Calibration corrections

Multiple smart low-cost air quality sensors co-located with a regulatory air quality monitoring station. By understanding how each unit performs relative to reference equipment, its data can be corrected to be a more accurate representation of reality. Image source: Creative Commons

Types of calibration correction

There are four main types of calibration correction.

1. Calibration correction for all devices of one type

Low-cost sensing devices can have a systemic bias in the data they report, relative to more accurate reference instruments. This is inherent to their design, and will be unique to each type of device on the market. Calibration correction of this kind involves adjusting data from all devices of one particular type, to ensure that the data reported is as accurate as possible. Typically, this is done by comparing data from a number of devices of one type to data from a trusted reference source. A fixed calibration correction for all devices of that type can be applied, either at the level of a device (i.e. within the firmware), or within the IoT platform that hosts the device.

2. Inter-device measurement variability correction

Individual sensing devices of the same type can vary in their performance, due to small variations in the manufacture and assembly of their components. For many device types, such inter-device measurement variation will be minimal, and is unlikely to pose a significant challenge to a smart sensing project. However, with many lowest-cost device options, this variation may be more pronounced. Depending on your data use case, you may need to formulate and apply a unique correction factor for every device in your network. To calculate this unique factor, you will need to co-locate each device prior to its main deployment. You can then apply the correction factor, either via the device firmware, or through a device-specific correction module within your Internet of Things (IoT) platform if your IoT Platform supports this.

3. Calibration drift correction

Sensing device performance may change over time, resulting in increasing loss of accuracy in a process called 'calibration drift'. This is caused by factors such as accumulation of dust, degradation of chemical cells, and ageing of sensor components. A calibration drift correction factor can be applied generically to a particular device type, either at device or platform level. This will ensure that sensor data is corrected over a defined operational period. Device types will have a maximum time period for effective drift correction, after which the correction factor is not able to compensate for the level of degradation that has occurred.

Many sensor manufacturers provide a drift metric as part of a device's specification sheet (expressed as a percentage loss of accuracy/time period). However, the rate of drift varies depending on environmental conditions; notably, it occurs faster at higher ambient temperatures. It is therefore advisable to establish your own drift correction metric that more accurately aligns with your local environmental conditions (which will likely vary from whatever standard conditions the vendor used to calculate the official specifications). The best way to achieve this is to permanently co-locate a device at a regulatory monitoring station, and keep it in place for the duration of your project. This allows you to track calibration drift over the longer term.

4. Calibration for different types of particulate pollution

The type and composition of pollution particles can substantially impact the performance of a low-cost particulate matter sensor, most of which report particle concentration based upon the measurement of light scattered off suspended particles. Variations in particle size, shape, mass, density, optical properties, and composition all alter how light is scattered off particles (Wallace et al. 2022). This, in turn, affects the concentration of particles that the sensor reports. These variations also change relative to background environmental factors like humidity. The outcome is that two types of particulate pollution with different properties (e.g. woodsmoke and diesel exhaust), measured at the same mass per square metre by a high-performance reference instrument, would be reported as two quite different masses by a low-cost optical sensor.

The implication for your sensing project is that if you are studying a specific type of particulate pollution with low-cost sensors, you should consider calibrating your device for that pollution type. Your device vendor may be able to assist you with this. Alternatively, you may need to develop a pollution-specific correction factor relative to your local environmental conditions.

Applying calibration corrections in your project

The calibration requirements for your project will vary according to:

- your data use case (which dictates the data quality you need to achieve)
- the context of your project (e.g. location or environment)
- the design of your project (e.g. device type, target pollutants, or device deployment methodology).

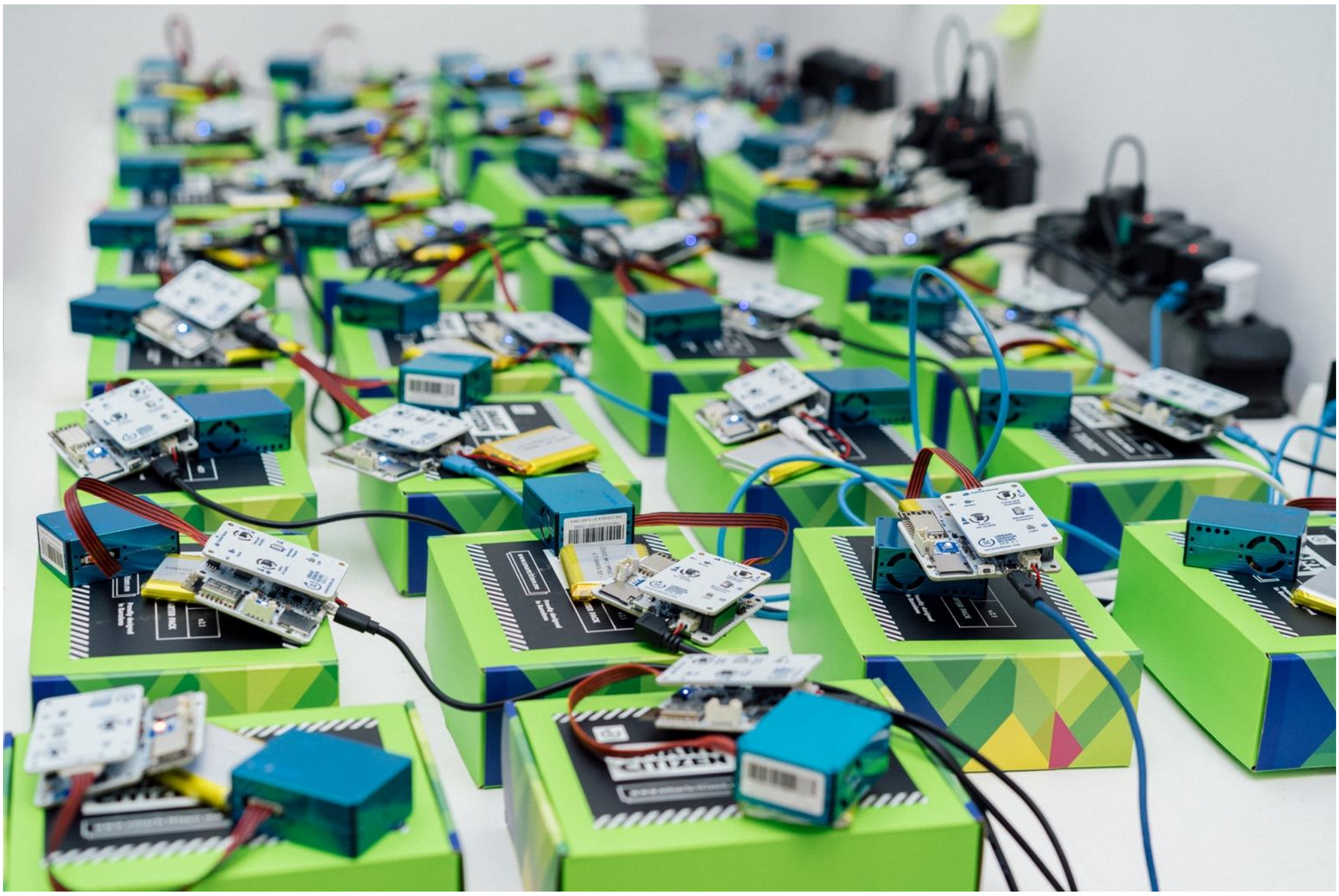

Image: Indoor co-location of Smart Citizen particulate sensors to assess intra-device variability. Image source: Creative Commons

General strategy

Calibration may need to be a continuous process

Ideally, calibration should be done before, during, and after sensing devices are deployed. This is because calibration requirements are influenced by temporal environmental factors (e.g. seasonal changes), or significant changes in the types of air pollutants being measured (e.g. during periods of heavy smoke). Calibration corrections may need to be regularly updated to keep in line with changing conditions, particularly in more dynamic environments.

Calibration should be done under the same conditions that you will operate the device

Due to changing environmental conditions and aerosol characteristics, there is a need for seasonal and/or source-specific calibrations. These can help improve the accuracy of low-cost sensors. Ideally, sensor calibration should be done under the same conditions (e.g. temperature range, humidity range, or concentrations of air pollutants) as the conditions in which the sensor will be deployed.

Methods for determining your own calibration factors

There are several approaches that you can take to determine calibration factors for low-cost sensing devices. Three recommended methods are:

- **Outdoor co-location** of low-cost sensing devices with high-quality reference instruments at a regulatory ambient air quality monitoring site. Detailed instructions for co-location are available from the relevant state environmental agency. You can also refer to the OPENAIR Best Practice Guide chapter *Sensing device calibration*.
- **Laboratory tests**, where low-cost sensing devices are compared to reference instruments under more controlled conditions (e.g. fixed temperature or humidity).
- **Indoor co-location** of multiple low-cost sensing devices, without reference equipment, to assess intra-device variability and check performance of each device relative to a mean. This method is imprecise and somewhat limited, but can be useful in more educational settings (see Tier I applications in the OPENAIR supplementary resource *A framework for categorising air quality sensing devices*).

Ensuring good calibration outcomes

If you are involved with leading or designing a smart sensing project, it is recommended that you understand calibration requirements at the general level described in this chapter. This will support you in making informed technology procurement decisions, and will help you design a sensing methodology that is appropriate to your data use case.

It should be noted that the level of support and sophistication relating to sensing device calibration among technology vendors varies considerably. Many ‘ultra-low-cost’ products come with no standard calibration corrections, requiring you to undertake corrections yourself. This may also mean that you need to do your own co-locations or lab tests. Other products may have more sophisticated pre-sale calibration processes, and built-in data corrections as standard. However, this may not rule out the need for running your own co-location tests if your use case demands high-quality data. During the procurement phase of your project, find out what level of support your chosen technology vendors provide, and ensure your needs can be met.

Environmental interference corrections

Examples of environmental interference corrections

Sensor response can be significantly influenced by environmental conditions, especially when there are extremes in either relative humidity (RH) or temperature. These are referred to as *environmental interference factors*, and they can be corrected for in the data. There are four notable types:

1. Temperature interference correction for gas sensors

Temperature has a significant effect on the function of low-cost gas sensors. These sensors operate through the reaction of a solid chemical cell with the gas that it is measuring. This reaction results in minute changes of voltage across the cell, which are interpreted as a relative concentration of the target gas. Chemical reactions happen faster at higher temperatures, meaning that a fixed gas concentration will be interpreted as more concentrated during hot weather, and less concentrated during cool weather. This effect may be mild at low temperatures, but increasingly pronounced at temperatures over 30°C or so. It is therefore important to understand the relationship between the output of a gas sensor, and the ambient temperature in which it is operating. This allows a temperature correction factor to be developed and applied.

Sensing devices should provide specifications for temperature correction. However, this relates to the function of a component sensor under laboratory conditions, and is unlikely to correspond with how that sensor will behave under deployment conditions. Once deployed, the complexity of other environmental factors may require you to consider developing a temperature interference correction factor that is formulated for your particular locality.

2. Temperature interference correction for particulate sensors

Depending on the type of aerosol source, different correction factors may apply. For example, for woodsmoke, the correction factor may be 0.5 (since woodsmoke particles are smaller and have less mass than other urban sources of particulates).

3. Humidity interference correction for particulate sensors

Pollution particles can attract or repel water droplets, which means that a variation in humidity can alter their size and mass, influencing the concentration of those particles that is reported by a low-cost sensor. Free-floating water droplets can also be recorded as pollution particles by low-cost sensors. The result is that a low-cost particulate sensor will report different particulate concentrations for a fixed amount of pollution at different relative humidities, requiring the application of a humidity correction factor. This correction factor may also vary by pollution type (e.g. woodsmoke may interact differently with humidity compared to vehicle emissions).

If you are measuring particulate pollution in an environment that experiences high humidity, it is advisable to develop a locally specific humidity interference correction factor that is formulated for the type of pollution you are studying. High humidity environments include low-lying riverine and coastal locations, often with a warmer climate, as well as cooler climates with high rainfall, or locations with fog and cloud (e.g. mountains and highlands).

If you detect a strong correlation of pollutant concentrations with humidity, you may set an upper limit for ambient humidity (e.g. greater than 75%-90% RH), above which particulate data would be discounted. This is an example of a rule that you might build into your data quality control process. Alternatively, you might develop and apply a unique interference correction factor for the subset of particulate data impacted by high humidity.

4. Salt aerosol interference correction for particulate sensors

In coastal environments, airborne salt particles can be detected by low-cost optical particulate sensors, and register as air pollution. This particularly applies to PM_{10} (larger particles, measuring ~10 microns across). In most cases, these salt aerosols will not be the subject of focus, so you will need to account and correct for them in your data. It is possible to determine a baseline correction for salt aerosols for a particular region. In some cases, the regulatory air quality monitoring authority may have a pre-determined regional correction for salt aerosols that can be applied. However, the most reliable approach is to undertake your own outdoor co-location with reference equipment to determine your own correction factor for your particular devices.

RELATIVE ACCURACY OF LOW-COST OPTICAL SENSORS

Low-cost optical sensors can potentially measure a range of particle sizes (e.g. PM_{10}, $PM_{2.5}$, and PM_1). However, low-cost sensors don’t measure all particulate size fractions well (for instance, PM_{10} is particularly difficult to detect accurately using low-cost sensors). This is partly due to the technology (e.g. frequency of light) that the sensors use to detect the presence of particulate matter. The approach taken to correction factors and calibration will be influenced by the particle size you are focused on measuring, as well as the design of your sensor.

Data harmonisation

Data harmonisation involves converting data expressed in different formats into a single, harmonised format (defined by a data schema). Large, harmonised data sets support improved analysis and better project outcomes. Harmonisation is also key to effective data sharing.

Data formats can vary due to differences in how sensor data is collected, labelled, and stored, and are influenced by the specifics of device types, device settings, sensing methodology, and the requirements of particular projects or data use cases.

Common factors to address with data harmonisation include units of measurement; decimal points; time and date formats; spatial co-ordinate formats; data labelling (metadata); and the way in which data is expressed by a particular computer coding language.

WHAT IS A DATA SCHEMA?
A data schema defines and characterises all the data used in a project, or within a particular platform. Each smart sensing project should develop its own data schema. A data schema defines two broad categories of data: telemetry and metadata.

- **Telemetry** refers to all dynamic information reported by a device, and includes sensor data (e.g. temperature), time/date, and device operation metrics (e.g. battery voltage and communications signal strength).
- **Metadata** is 'data about data', and is defined by 'fields', each of which describes a specific attribute of your data (or other aspects of your project).

For detailed guidance on developing a project data schema, please refer to the OPENAIR Best Practice Guide chapter *Data labelling for smart air quality monitoring*.

When do you need to harmonise data?

There are two common scenarios in smart low-cost air quality sensing that require data harmonisation.

1. Harmonisation for hybrid device networks

Hybrid networks incorporate two or more device types within the same network. In this case, data harmonisation is required within one's own data management system, using a project-specific data schema. Examples of why this might be desirable include:

- Two types of device might report **the same environmental parameter** (e.g. ambient temperature), but express it in different ways. It would be desirable to harmonise the environmental telemetry from both devices, enabling direct comparison and the creation of a larger, merged data set.
- Two types of device might report **the same operational telemetry** (e.g. battery voltage and communications signal strength), but express it in different ways. It would be desirable to harmonise operational telemetry to support a single approach to device management for all device types on a network. This streamlines operations, reduces issues and loss of data, and saves money.

2. Harmonisation for data sharing

When multiple organisations share data into a central data aggregation platform or portal, the chances are high that each data set (or stream) will have unique properties. Such a platform needs to harmonise all the data it ingests, so that it may be directly compared or merged. For example, a state government agency might develop a platform for the sharing and exchange of air quality data produced by local governments. That platform would host a data schema that defines a single, harmonised format for all telemetry and metadata entering it. Harmonisation would allow air quality data from two different local governments to be directly compared, and for that local government data, in turn, to be compared with data from regulatory monitoring stations.

Units of measurement

Air pollutants are measured and reported in a range of different units. In general, particles are reported in micrograms per cubic metre ($\mu g/m^3$), and gases (e.g. CO) in parts per million (ppm), parts per hundred million (pphm), or parts per billion (ppb). The choice of unit depends on factors such as the type of pollutant, the measurement technique, and the performance of the sensor.

The NSW Department of Planning and Environment provides helpful information on [measurement units and conversion factors,] so that you can convert your data and compare it to other sources of information.

Other units of measurement to consider include time and date format, and spatial co-ordinates. Refer to the OPENAIR Best Practice Guide chapter *Data labelling for smart air quality monitoring* for more detailed information on these topics.

Averaging Periods

Low-cost sensing devices report air quality data readings periodically, at a rate defined by the device manufacturer (e.g. every 5, 15, or 60 minutes). This is known as the 'reporting interval'. Air quality data that is visualised, shared, or otherwise utilised in some way is almost always averaged across a standard time period known as an 'averaging period'. The averaging period is distinct from the reporting interval, and is often longer (though never shorter).

Commonly used averaging periods

Table 1 below provides a list of commonly used averaging periods. Note that an averaging period of less than 1 hour is possible, and may make sense for many low-cost sensing applications. However, sub-hourly periods are not used by regulatory authorities, so you cannot compare sub-hourly data to regulatory data.

Table 1. Commonly used averaging periods

Time period	Application
1 minute average	Low-cost sensing only
10 minute average	
1 hour average	Regulatory monitoring data *AND* Low-cost sensing data
4 hour rolling average	
8 hour rolling average	
24 hour rolling average	
Monthly average	

What averaging period should I use for my project?

Different averaging periods are appropriate for different types of study and data use cases, for example:

- Highly localised peak pollution events that occur over short periods (such as peak traffic at a specific road intersection) may require the use of very short averaging periods (e.g. sub-hourly)
- For reduction of personal exposure by modification of activity patterns, hourly average concentration data is recommended
- For research into the daily exposure of residents to ambient pollution at the scale of a precinct or suburb, longer averaging periods would be more appropriate (e.g. 4, 8, or 24 hours).

Device providers (and their associated platforms) may provide you with options for accessing, downloading, or sharing data with different averaging periods. You should consider this as part of your technology procurement decision-making.

Advantages of longer averaging periods

Advantages of longer averaging periods include:

- **Reducing noise.** Longer averaging periods smooth data over time, so that peaks and troughs are less pronounced. This can help to remove 'noise' associated with chaotic variations and complexity in a data set, providing a more stable overall trend.
- **Aligning with exposure guidelines.** National and state guidelines for the health implications of various air pollutants are expressed as Air Quality Categories according to pollutant concentration thresholds relative to averaging periods (e.g. a recommended upper threshold for 'Good' PM2.5 is 25µg/m^3 over a 1 hour averaging period). Your data averaging periods may be shorter or longer depending on your needs. These guidelines may use different averaging periods than you might otherwise choose to calculate for your own low-cost sensor data.

Disadvantages of longer averaging periods

Disadvantages of longer averaging periods include:

- **Missing short-term peaks in pollution.** Peak pollution events may be overlooked if they occur over periods that are shorter than the averaging time used (e.g. the peak concentration of a 15-minute pollution event would not be represented in an hourly average for that period).

TIP: Averaging periods must match if you want to compare data
Air quality data for a particular pollutant can only be compared between two locations if averaging periods for both data sets are the same.

AVERAGING PERIODS STRONGLY INFLUENCE DATA VISUALISATION
The longer the averaging period, the 'smoother' your data will appear. The below graph shows $PM_{2.5}$ concentrations plotted with different averaging times, illustrating how different data can look when plotted using 1-hour, 24-hour, and monthly averaging periods. (Data from Parramatta North, NSW)

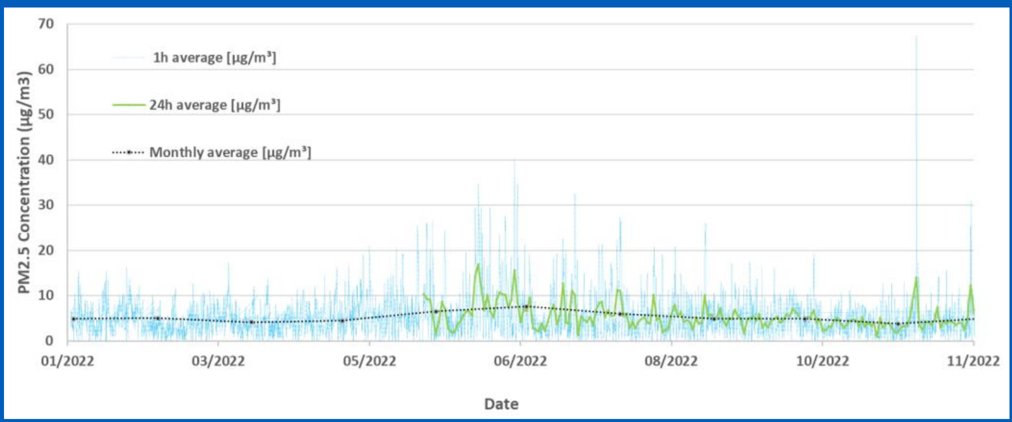

Figure 2. Examples showing how averaging at different timescales removes fluctuations and extremes in data resulting in an overall trend. Figure source: (Data from Parramatta North, NSW)

Aligning data harmonisation with existing standards and practice

It is important to be aware of existing standards and practice for air pollution monitoring and reporting that apply in your region, as you may want to align your data harmonisation with these.

Australia's National Environment Protection Measure (NEPM) for Ambient Air

In Australia, the standards for 'priority' air pollutants are reported in the National Environment Protection Measure (NEPM) for Ambient Air. The NEPM standardises how air quality data should be formatted and labelled at state and national level, and should inform the design of your own project data schema.

You may wish to associate your air quality data with health risk. The NEPM defines how to calculate AQI (Air Quality Index) values, which provide an overall indication of air quality health risk, based on the concentrations of multiple air pollutants. AQI definitions and values are categorised from 'Very Good' (0–33), to 'Fair' (67–99), to 'Hazardous' (200+). These categories can be used to plan activities and protect the health of citizens. AQI is used by many Australian states and territories (e.g. the ACT), but not in New South Wales.

New South Wales (NSW) standards and practice

Figure 3. The NSW Government's scale of air quality. Figure source:(NSW Department of Planning & Environment, n.d.)

The NSW Government runs a state-wide network of regulatory ambient air quality monitoring stations that collect and report hourly data for ozone (O_3), nitrogen dioxide (NO_2), visibility, carbon monoxide (CO), sulphur dioxide (SO_2), and airborne particles ($PM_{2.5}$ and PM_{10}).

In NSW, AQI has been replaced by Air Quality Categories (AQC), which apply ratings of 'Good' through to 'Extremely poor' (defined by concentration threshold values) for each of the pollutants measured. AQCs have the advantage of applying to each pollutant individually, which can be helpful to local authorities wishing to focus on a particular type of air pollution and its health implications.

The NSW Government provides general health advice and recommended actions relative to AQCs in their Health Activity Guide. Guidelines advise when people should 'reduce' or 'avoid' strenuous outdoor activity, and when to 'stay indoors'. The NSW Government also issues direct air quality alerts on days when pollution levels are forecast to be "Poor" worse.

Local governments in NSW may wish to format and present their own air quality data so that it aligns with reported regulatory data, the Air Quality Categories, and associated health alerts (for instance, by using the same specified units of measurement, decimal points, and averaging periods).

YOUR DATA INTERPRETATION JOURNEY: CHECKPOINT 1

At this point in your data interpretation journey, you should check that:

- your data is corrected to a quality that meets the needs of your data use case and your planned data sharing activities
- multiple data streams within your own platforms have been harmonised to support value creation and operational efficiency (if relevant to your project)
- your data harmonisation aligns with any external data sharing platforms, and with the needs of a broader community of data users (if you are sharing data with other groups or organisations).

References

NSW Department of Planning & Environment. (n.d.). *Air quality alerts*. https://www.dpie.nsw.gov.au/air-quality/air-quality-alerts

Wallace, L., Zhao, T., & Klepeis, N. E. (2022). Calibration of PurpleAir PA-I and PA-II monitors using daily mean PM2. 5 concentrations measured in California, Washington, and Oregon from 2017 to 2021. *Sensors* 22(13), 4741, https://doi.org/10.3390/s22134741

Zimmerman, N. (2022). Tutorial: Guidelines for implementing low-cost sensor networks for aerosol monitoring. *Journal of Aerosol Science* 159, 105872, https://doi.org/10.1016/j.jaerosci.2021.105872

Additional resources

Australian Government* | *National Environment Protection (Ambient Air Quality) Measure

Provides details of averaging times for each pollutant, and thresholds for maximum concentrations (see *Schedule 2: Standards and Goals*).

NSW Department of Planning and Environment* | *Air quality data averaging periods

Provides information on the NSW State Government's approach to averaging periods.

U.S. Environmental Protection Agency* | *Air Sensor Toolbox

The U.S. Environmental Protection Agency (EPA) has developed extensive guidance on the use of low-cost sensor data, including a range of information on how to understand your sensor data readings.

U.S. Environmental Protection Agency* | *Instruction Guide and Macro Analysis Tool: Evaluating Air Sensors by Collocation with Federal Reference Monitors

A detailed instruction guide on how to co-locate low-cost air quality sensing devices with federal reference monitors (FRM) in the United States. This resource includes an Excel-based Macro Analysis Tool.

Zimmerman, N. (2021) | Low-Cost PM Sensor Tutorial

This tutorial provides instructions, practical tools, and downloadable code to assist with the assessment and calibration of data from low-cost air quality sensing devices.

Associated OPENAIR resources

Best Practice Guide chapters

Data interpretation: overview

This Best Practice Guide chapter provides guidance for interpreting data produced by smart low-cost air quality sensors. It outlines the three main stages of the process (data correction and harmonisation; data quality control; and data analysis), explores the relationship between data interpretation and impact creation, and supports the planning of a data interpretation strategy.

Data interpretation: quality control

This Best Practice Guide chapter provides guidance for the quality control of data produced by smart low-cost air quality sensors. Data quality control helps to isolate trusted data that can then be used to support chosen activities. This chapter explores approaches for cleaning static data sets to prepare them for analysis, and approaches for operational verification and quality control of live data streams.

Data interpretation: analytics

This Best Practice Guide chapter introduces common analytical approaches that can be applied to data produced by smart low-cost air quality sensors. These include statistical analysis; temporal interpolation; spatial aggregation and interpolation; complex geospatial system modelling; and AI and machine learning applications.

Sensing device calibration

This Best Practice Guide chapter provides practical guidance on the calibration of smart low-cost air quality sensing devices. It discusses calibration, co-location, decision-making, and developing and undertaking a plan.

Data labelling for smart air quality monitoring

This Best Practice Guide chapter provides guidance on data labelling for smart air quality monitoring. It provides advice for developing and implementing a project data schema, which defines all the telemetry and metadata that will be used in a project.

Supplementary resources

A framework for categorising air quality sensing devices

This resource presents a new framework for categorising air quality sensing devices in an Australian context. It identifies four tiers of device types, separated in terms of functionality, and the quality and usability of their data output. It is designed to assist with the selection of devices that are appropriate to meeting the needs of a project and an intended data use case.

Further information

For more information about this project, please contact:

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This Best Practice Guide section is part of a suite of resources designed to support local government action on air quality through the use of smart low-cost sensing technologies. It is the first Australian project of its kind. Visit www.openair.org.au for more information.

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