AFFORDABLE COVERAGE WITHOUT COMPROMISE: CORRECTING LOW-COST PARTICULATE MATTER SENSORS FOR REAL-WORLD CONDITIONS

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Abstract (Abstract heading style)

Managing particulate matter emissions from operational sites demands monitoring networks that are both spatially comprehensive and capable of triggering real-time adaptive management. While near-reference instruments deliver high measurement accuracy, their substantial cost constrains deployment density and geographic coverage. Low-cost sensors offer a promising alternative to expand spatial resolution. However, limitations of these instruments include the absence of heated inlets and lower precision, making them susceptible to humidity-driven hygroscopic interference and data quality challenges.

This study evaluates the effectiveness of a hybrid continuous particulate matter monitoring network over a twelve-month operational period, with quarterly collocation undertaken to assess seasonal variability and prevent data drift. The network comprised one MCERTS-certified near-reference monitor (Aeroqual Dust Sentry PCX) with a heated inlet and three low-cost indicative monitors (Quant-AQ Modulair-PM). To address inter-sensor variability and hygroscopic growth artefacts, a site-specific Lookup Table (LUT) was constructed by correlating near-reference measurements against a collocated low-cost sensor across discrete internal temperature and relative humidity bins. A dedicated week-long collocation period for all low-cost units was then used to derive unique scalar multipliers quantifying individual sensor sensitivity offsets relative to the network baseline.

Data analysis revealed that uncorrected low-cost sensors systematically overpredict PM_{10} concentrations under low-temperature, high-humidity conditions, while underpredicting during warm, dry periods. Critically, seasonal variations were found to significantly alter sensor response, necessitating quarterly LUT recalibration, and collocation analysis revealed substantial inter-unit variability in sensor sensitivity, requiring unique correction factors for each unit. These findings demonstrate that low-cost sensors, supported by dynamically updated and seasonally responsive correction frameworks, can meaningfully expand hybrid dust monitoring networks to produce representative datasets capable of reliably triggering operational alerts and offering a scalable, cost-effective solution for real-time emissions management.

Keywords: *particulate matter; low-cost sensors; hygroscopic correction; dust monitoring.*

1. Introduction

A wide range of industrial and operational activities generate fugitive particulate matter (PM), from vehicle movements, material handling, and wind erosion of exposed surfaces. Real-time continuous monitoring is increasingly essential to underpin Trigger Action Response Plans (TARPs). This enables on-site personnel to implement dust mitigation measures when applied concentration thresholds are exceeded. Effective TARP application demands both spatial coverage and high measurement quality to minimise the frequency of false alarms or missed exceedances.

Reference-grade instruments such as a tapered element oscillating microbalance (TEOM) or beta-attenuation monitor require air-conditioned housing and mains power. These requirements, together with their high cost, limit where the instruments can be sited and therefore constrain measurement of a site's contribution to ambient particulate concentrations. Near-reference instruments offer an alternative to reference-grade instruments, providing excellent accuracy. The cost of these instruments

can typically exceed $20,000 AUD, meaning that the use of multiple instruments around a site can be cost prohibitive for operations, which typically limits practical deployment of the instrumentation to a single location.

Low-cost sensors (LCS) operating on the optical particle counter (OPC) principle offer an affordable alternative at approximately $2,000 – $5,000 per unit, enabling multi-point spatial networks. However, LCS exhibit inherently lower accuracy and precision than reference and near-reference instruments, and units without heated inlets are additionally susceptible to hygroscopic particle swelling at elevated relative humidity (RH), biasing measured concentrations. Manufacturing variability also introduces unit-specific sensitivity differences that compound measurement uncertainty.

This paper presents a two-stage sequential correction framework applied to a hybrid monitoring network consisting of one near-reference MCERTS-certified instrument and three LCS units deployed across a distributed, multi-point network. Drawing on two consecutive quarterly monitoring periods spanning the cooler and warmer halves of the year, the seasonal behaviour of the correction factors is examined, establishing how the calibration can be maintained on the fly so that a distributed network remains fit for real-time dust management.

2. Monitoring Network

2.1. Site and Instrumentation

Monitoring was conducted at an operational, dust-generating industrial site in Victoria, Australia. Three monitoring locations (AQ1, AQ2, AQ3) were established based on the positions of on-site dust-generating activities and the proximity of sensitive residential receptors, with the nearest located a few hundred metres from the site boundary.

The near-reference instrument, an Aeroqual Dust Sentry PCX (MCERTS-certified) was deployed at AQ1, collocated with a Quant-AQ Modulair-PM LCS. The Aeroqual features a heated inlet (preventing hygroscopic bias), a built-in AirMar200 meteorological sensor, and continuous 1-minute measurements of particulate matter with an equivalent aerodynamic diameter of 2.5 micrometres or less ($PM_{2.5}$) and 10 micrometres or less (PM_{10}). AQ2 and AQ3 operated as spatially independent LCS-only locations, powered by solar PV and streaming real-time data to cloud dashboards. AQ3 was positioned upwind of site operations to serve as a background reference.

Both the Aeroqual and Modulair-PM instruments measure $PM_{2.5}$ and PM_{10} at 1-minute resolution. The Aeroqual PCX module specifies an accuracy of <5% of reading and a precision of approximately ±3% (3.1% for $PM_{2.5}$ and 2.3% for PM_{10}), with a lower detectable limit of 0.1 $\mu g/m^3$ – 0.3 $\mu g/m^3$ (Aeroqual, 2026). The Modulair-PM units are indicative-grade, with reported unit-to-unit precision of the order of 3% for $PM_{2.5}$ and 6% for PM_{10} and, as with most unheated OPC sensors, are susceptible to humidity interference above approximately 90% relative humidity (Quant-AQ, 2026).

The key particulate size fraction for this industrial site is PM_{10}, as material handling, wheel generated dust from roads and windblown dust are largely associated with PM_{10}. Additionally, no trigger level has been applied to the $PM_{2.5}$ pollutant at this industrial site. Hence, the focus for this paper is centred around PM_{10}.

2.2. Regulatory Trigger Framework

In Victoria, operational sites of this kind typically operate under an Risk Management and Monitoring Program (RMMP) which typically includes an Adaptive Dust Management Plan (ADMP) and an associated TARP, which define the trigger levels the monitoring network must resolve. EPA Publication 1961.2 suggests that PM_{10} trigger levels are set at 80 µg/m3 (1-hour average), 120 µg/m3 (30-minute average), 150 µg/m3 (15-minute average) or 165 µg/m3 (10-minute average) (VIC EPA, 2025). The intent of these trigger levels is to ensure compliance with Victorian EPA Environment Reference Standard (ERS) objective for 24-hour average PM_{10} of 50 µg/m3 (VIC EPA, 2021).

3. Correction Methodology

3.1. Stage 1: Hygroscopic Lookup Table (LUT)

Unheated OPC-based sensors are susceptible to hygroscopic particle swelling: at elevated RH, liquid water condensing on particle surfaces increases apparent mass, inflating measured PM concentrations. The magnitude of this bias is jointly determined by temperature (which governs vapour pressure and water activity) and RH, which together require a two-dimensional correction surface rather than a simple RH threshold.

A site-specific LUT was derived from continuous collocation of the AQ1 Modulair-PM unit with the Aeroqual reference at the AQ1 monitoring position. Correction factors (CF) were calculated as the median ratio of Aeroqual PM to AQ1 PM, the median being used in preference to the mean for robustness against outliers, within discrete internal temperature (0°C – 50°C) and internal RH (0% – 90%) bins at fixed, fine increments, using hourly rather than 1-minute ratios to reduce high-frequency noise in the CF. Bins containing too few observations for a robust estimate were assigned a default CF of 1.0 (no correction). To prevent unstable corrections in

sparsely populated bins, empirically determined maximum CF limits were applied. The resulting LUT characterises sensor response deviation under all meteorological conditions experienced during the quarter.

3.2. Stage 2: Inter-Sensor Scalar Calibration

Hardware manufacturing variance introduces unit-specific sensitivity differences that persist after hygroscopic correction. To quantify and remove these offsets, a dedicated one-week collocation period was conducted for each quarterly dataset, during which AQ2 and AQ3 were physically relocated to operate side-by-side with AQ1.

A forced zero-intercept linear regression was applied to LUT-corrected 1-hour data: the slope of each target sensor regressed against AQ1 yielded a scalar multiplier expressing its sensitivity offset relative to the network baseline (AQ1). The intercept was forced through the origin because a sensor reading zero concentration should, by definition, correspond to zero at the baseline. As the collocation is a fixed-duration field exercise rather than a rolling monitoring window, no minimum data-completeness threshold was applied to the regression dataset. Table 1 presents the Q2 scalar factors. AQ3 showed the smallest PM_{10} scalar (0.615), reflecting that without correction, an over-report of PM_{10} by approximately 63% would be reported. Additionally, AQ2 over-reports PM_{10} by approximately 33%. $PM_{2.5}$ scalars were closer to unity, indicating smaller inter-unit $PM_{2.5}$ sensitivity differences.

Table 1. Inter-sensor scalar CF derived from the quarterly collocation.

Instrument	$PM_{2.5}$ Scalar	PM_{10} Scalar
AQ1	1.000	1.000
AQ2	1.119	0.750
AQ3	0.982	0.615

3.3. Application Pipeline

Corrections were applied sequentially at 1-minute resolution to preserve the full T/RH signal before it is attenuated by time-averaging. The pipeline comprised: (1) LUT hygroscopic correction applied to raw 1-minute data; (2) scalar multiplication applied to LUT-corrected values; (3) a physical sense check enforcing $PM_{10} \geq PM_{2.5}$ at each time step; and (4) time-averaging to 15-minute, 1-hour, and 24-hour intervals, each requiring ≥75% valid data coverage (≥12/15 min, ≥45/60 min, or ≥18/24 hr, respectively) (NEPC, 2001). Negative sensor readings were set to zero, and data where internal RH exceeded 90% were excluded prior to LUT application to eliminate saturated-sensor artefacts.

The Q2 CFs were also applied retrospectively to ensure consistency; real-time TARP monitoring during Q2 used Q1 CFs (the only available seasonal data at that time). Data collected during a collocation period were excluded from that quarter's monitoring dataset, as the units were physically relocated and not sampling their deployment positions.

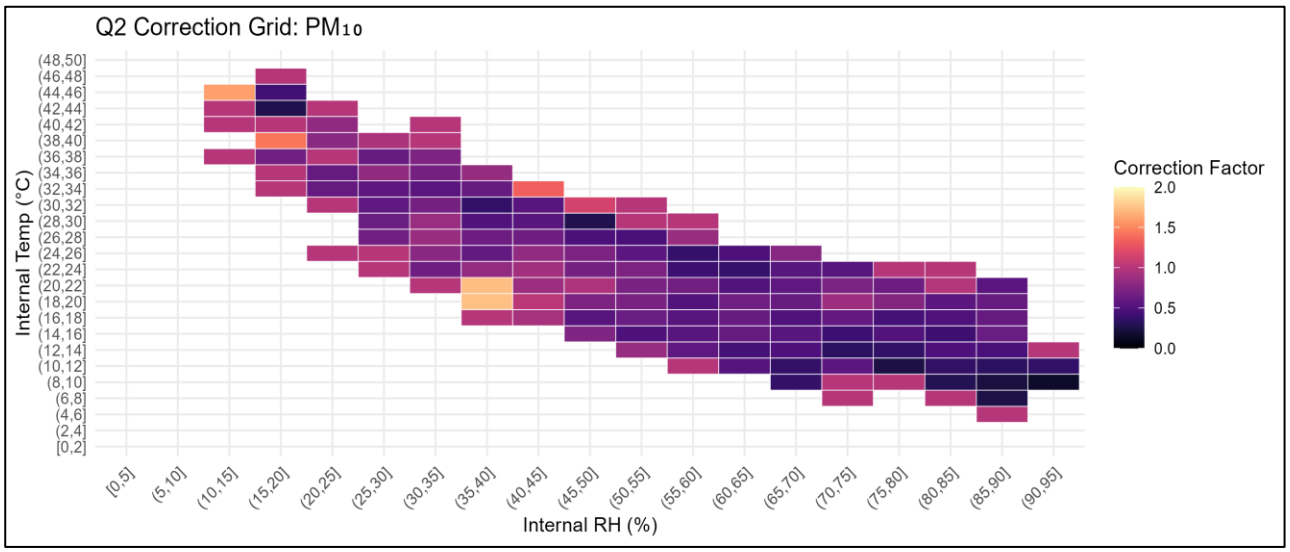


Figure 1. PM_{10} LUT correction surface collocated hourly data, and time series of raw, LUT-corrected, and reference PM_{10} over a single monitoring quarter. Darker colours (CF approaching 0) indicate overprediction of PM_{10} at low temperatures and high RH; warmer colours (CF > 1) indicate underprediction at higher temperatures and low RH.

4. Monitoring Network Performance

4.1. Data Completeness

Adequate data completeness is a prerequisite for reliable network operation. A minimum of 75% valid data within each averaging period is a widely applied threshold for ambient monitoring (NEPC, 2001), with periods falling below this excluded from analysis. Solar-powered LCS nodes are particularly prone to data gaps, as limited battery reserve can interrupt logging during overnight and early-morning periods of low charge. Such losses typically cluster at particular times of day rather than occurring at random, whereas mains-powered near-reference instruments are generally more robust in this respect. Sustaining completeness across a distributed LCS network therefore requires attention to power provisioning and periodic connectivity checks, with occasional gaps anticipated and managed rather than treated as exceptional.

4.2. Seasonal Variability in Correction Factors

Comparison of Q1 and Q2 LUTs revealed meaningful seasonal differences. The Q1 LUT (winter/spring) was characterised by low temperatures and a narrower RH range, while the Q2 LUT (spring/summer) captured higher temperatures and broader RH variability. These differences in populated T/RH bins confirm that a static LUT would fail to represent seasonal aerosol-water interactions accurately, supporting the need for quarterly recalibration.

In contrast, the inter-sensor scalar multipliers showed strong temporal stability: Q1-to-Q2 variation was only 0.01 – 0.07 across all instruments and pollutants, with the largest change observed for AQ2 $PM_{2.5}$ (approximately +0.07 from Q1 to Q2). This indicates that LCS sensitivity offsets are primarily a hardware characteristic rather than an environmentally driven response, and quarterly collocation is adequate to maintain scalar accuracy.

5. Discussion

The sequential two-stage framework offers practical and conceptual advantages over single-step regression approaches. By explicitly separating the physical (hygroscopic swelling) from the instrumental (sensitivity offset) error source, each correction stage can be independently derived and updated. Applying the hygroscopic correction at 1-minute resolution before time-averaging is critical: aggregating first and then correcting would attenuate the T/RH signal that drives the hygroscopic correction, reducing its effectiveness during periods of rapidly changing atmospheric conditions.

The directional asymmetry of the hygroscopic bias (overprediction at high RH and underprediction under warm, dry conditions) is consistent with the known behaviour of OPC-based sensors. At high RH, absorbed water increases particle scattering cross-section, causing inflated counts: application of a CF of <1 appropriately deflates these values. The temperature dependence of this effect explains the two-dimensional LUT structure, and the seasonal shift observed between Q1 and Q2. Applying a one-dimensional RH correction alone would introduce systematic temperature-dependent residuals.

The wide disparity in PM_{10} scalar values (AQ3: 0.615; AQ2: 0.750) highlights the importance of individual unit characterisation. Deploying LCS units without this step would introduce systematic biases of 33% – 63% relative to the network baseline. The smaller $PM_{2.5}$ scalars (within 12% of unity) suggest that inter-unit variability is more pronounced for larger particle fractions, consistent with greater sensitivity of PM_{10} optical response to differences in detection chamber geometry. These scalar factors, however, capture more than hardware variance alone. Because OPC-based sensors infer mass from particle scattering, the derived sensor response also depends on the size distribution, composition and refractive index of the sampled aerosol (Crilley et al., 2020). The collocation therefore aligns each unit not only to the network baseline but to the reference under site-representative particle conditions, meaning the reported multiplier embeds a site-specific component that cannot be distinguished from the underlying instrumental offset. This means that scalar factors need to be developed on a site-by-site basis.

Beyond improving measurement accuracy, the correction framework directly improves the reliability of trigger-based responses. Uncorrected LCS data biased high under cool, humid conditions can generate false trigger exceedances, prompting unnecessary mitigation and eroding confidence in the network. Conversely, underprediction in warm, dry conditions risks missing genuine exceedances. By removing both the hygroscopic and inter-unit sensitivity biases before data are averaged against trigger thresholds, the framework reduces both false alarms and missed exceedances. This allows on-site personnel to act on trigger alerts with greater confidence that they reflect real changes in ambient dust rather than sensor artefacts.

A limitation of the framework is that LUT reliability is dependent on the density of data populating each T/RH bin. Sparse bins default to CF = 1.0, which may underestimate correction in the less frequently encountered meteorological conditions. As the dataset grows over successive quarters, LUT confidence will increase. Ultimately, after four

complete seasonal quarters, a full-year LUT could replace the rolling quarterly approach.

6. Conclusion

This paper demonstrates that a hybrid monitoring network comprising a single MCERTS-certified near-reference instrument and three low-cost OPC-based sensors, supported by a seasonally adaptive two-stage correction framework, can produce representative operational datasets for real-time dust management. Key conclusions are:

(1) A T/RH-binned hygroscopic LUT is essential and must be updated quarterly to capture seasonal changes. The LUT must be applied at 1-minute resolution before any time-averaging to preserve its effectiveness.

(2) Individual sensor scalar calibration from collocation can correct inter-unit PM_{10} sensitivity offsets of up to 63%, offsets that would otherwise render raw or uniformly corrected LCS data unreliable for compliance and trigger assessments. Scalar factors showed strong quarterly stability, suggesting that quarterly collocation is sufficient.

(3) By removing hygroscopic and inter-unit biases before data are compared against trigger thresholds, the corrected network reduces both false alarms and missed exceedances, improving the reliability of real-time trigger responses and operator confidence in the data.

(4) The methodology is broadly transferable to other operational facilities requiring spatially distributed, real-time PM monitoring under dynamic environmental conditions.

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