University of Newcastle

Final Report

Project title: Integration of Real-Time Low-Cost Particulate Matter Sensors into Coal Mining Air Quality Management to Identify Sources and Reduce Hazardous Exposure
Chief investigator: Dusan Ilic
Grant number: 20657

Alex Lavrinec and Dusan Ilic
21 June 2023/Modified for distribution May 2024

Executive Summary

Air quality and workplace exposure are both important considerations in open-cut coal mining. Regulation typically involves a few expensive reference monitors located at the boundary, assessing hourly and daily concentrations while workplace exposure is assessed once or twice a year. Controlling associated environmental and health risks is typically instigated by subjective operator judgement. Low-cost, portable sensors can supplement these methods to increase both spatial and temporal resolution at a fraction of the cost. Bespoke low-cost autonomous units were built. The units are solar powered with battery backup and can be deployed in minutes. Each unit samples, averages and sends data to a gateway with the data visualised on an online dashboard. More than a dozen sensors were deployed, and particulate matter dust emission data collected from different areas of the mine, over a period of four months. Easy installation and quick sampling rate enabled assessment of instantaneous dust generation, in close vicinity to mining activity. Different areas showed periods of similar but also varying particulate matter concentrations. From the first deployment over a period of seven weeks, a specific location showed more than six times difference in average weekly PM_{10} concentrations. From the second deployment over a period of approximately one month, in one instance a specific location recorded more than fifty times the average daily PM_{10} concentration recorded at a different location. A real-time system to supplement existing boundary and personal monitors is demonstrated to work. The network of sensors can lead to more data-driven decision making with minimised subjectivity and can be integrated into a dust management and action plan that can reduce operational downtime due to regulatory exceedance and occupational risk.

Contents

Executive Summary 1
Project milestones 3
Introduction 3
Background 3
Aims and objectives 4
Sensor unit description and functionality 4
Unit components and specification 4
Indoor deployment 7
Results 9
Outdoor deployment 10
Results 12
First deployment 12
Second deployment 13
Targeting specific areas 15
Accuracy assessment 20
Co-location setup 20
AS 3580.9.17:2018 procedure 21
Between instrument uncertainty 22
Expanded relative uncertainty 24
Conclusion 29

Project milestones

- By First (October 2023) Progress Report
    - Select, assemble, and test individual low-cost sensor (LCS) unit components including PM sensor, microcontroller, power source, communication module and weather-proof case.
    - Trial array of LCS units in pilot scale study in industrial workplace of high activity of bulk solid sample preparation and testing (e.g., NIER) to investigate linking specific activities to PM emissions.
    - Develop an interface to visualise PM emissions data, sources, and early warning.
- By Second (March 2023) Progress Report
    - Assess the sensors using a modified procedure to that outlined in AS3580.9.17.
    - Deploy LCS units (e.g., several units in an array) at an open-cut mine for real-time, continuous site monitoring.

Introduction

Background

The general approach to managing dust emissions due to mining activity includes measuring air quality dust concentration, deposition, as well as use of factors and meteorological data to predict emissions. Dust concentrations are generally assessed in terms of suspended particulate matter (PM) with an aerodynamic diameter below 10 µm and 2.5 µm, (PM10 and PM2.5 respectively). Standard, reference grade or equivalent methods such as high-volume air sampling (Hi-Vol), Tapered Element Oscillating Microbalance (TEOM) and Beta Attenuation Monitor (BAM) are expensive to install and operate. These devices involve drawing a sample of air through an inlet in a specific location and measuring PM concentration. However, typically, dust monitoring is limited to only a handful locations, limiting spatial resolution and these methods are expensive both with regards to capital and operating costs. Workplace dust monitoring may also be regarded as infrequent, generally occurring a few times a year.

Australian air quality regulations generally align with US and European environmental agencies, with the basis generally referencing US EPA classification. A three-tiered air quality monitoring approach involves reference methods (regulatory monitoring, 10% precision and bias error) as the regulation standard, followed by near-reference (supplemental /personal exposure, 20-30% precision and bias error) and indicative (education, hot spot identification, 30-50% precision and bias error). Recent advancement of technology, coupled with affordability, has seen increasing use of low-cost sensors (LCS) to monitor local air quality in urban settings and by individual businesses. However, unlike expensive reference methods, an application, standard use, and certification framework for the use of LCS in air quality monitoring is not yet in place. This has exacerbated uncertainty regarding LCS accuracy, purpose, operation, and calibration.

LCS may be viewed as affordable for personal use (AUD$150 to AUD$2,000) sensors that use light scattering technology which results in lower accuracy compared to more established versions employing the same or similar technology such as the DustTrak for example. However, despite lower reported accuracy, both the US EPA and the European Committee for Standardization (CEN) have studied and promoted LCS in an effort towards developing a framework for their application as supplemental, for research and education, while accepting that their intended application is unlikely to rival or replace standard or equivalent reference methods. Neither organisation provides a specific definition of what a LCS is defined as, however, both infer these are emerging, low prices sensors.

The consequences of ineffectively managing dust emissions include reduced air quality that can result in illness in the surrounding communities and chronic diseases such as black lung and silicosis that can manifest in workers. Typically, emissions are controlled by adding water, which is a scarce resource and ensuring its use is effectively integrated into dust management is crucial in minimising environmental impact. Controlling environmental and health risks is also typically instigated by subjective operator judgement. Low-cost, portable sensors can supplement regulatory methods to increase both spatial and temporal resolution at a fraction of the cost.

Aims and objectives

The main aim of the project is to demonstrate that a real-time measurement system comprised of an array of LCS units can be used as complementary to the existing dust monitoring and management techniques. This aim will be fulfilled through the following objectives:

- Select, assemble, and trial individual LCS units tailored made for deployment on a mine site.
- Trial the LCS units in an indoor environment that has dust generating activities that can be targeted.
- Develop a method to undertake accuracy and calibration check of the LCS co-located with a reference or a near-reference method.
- Trial the LCS units on a mine site with environmental management in mind, i.e., monitoring various locations on a mine site, gathering spatial data.
- Trial the LCS units on a mine site with occupational workplace exposure and health in mind, i.e., targeting specific activities involving workers outside of cabs.

Sensor unit description and functionality

In the interest of brevity, only the final iteration of the sensor unit is described in detail. The previous iterations are briefly outlined, but in essence, the evolution of the units started from the most basic unit capable of only reading PM data and sending it remotely. The units were then upgraded to include all the other functionality in steps – battery and solar power, GPS, ease of assembly, heated inlet, etc.

The basic idea of the implementation is taking readings every 2-5 seconds, average them out, send the average every 1-2 minutes. The average gets received at the gateway that is connected to the internet and the data is then visualised and made accessible.

Unit components and specification

The specification of the units is now present as a list of components with brief description of the component, specific role or capabilities, key specifications reasons for selection and other major considerations. This is provided to demonstrate and document the methodology adopted, challenges and benefits of various components and choices made during this project. The major components are shown in Figure 1.

- PM sensor – Plantower PMS5003.
    - By far the most popular sensor unit in this space both in commercial implementations and research.
    - Works by drawing in air using a little fan, the air then goes through the sensing part where a laser shines a beam that is scattered by the particles within the air stream. A photodiode then takes a measurement of the scattered light which is then translated into PM values.
    - Can read up to 1000 μg/m³ in all three PM fractions – PM_1, $PM_{2.5}$ and PM_{10}
    - The fan consumes most of the power. Overall, the sensors consume around 0.2 W.
- Microcontroller and communications – ESP32-32U.
    - These microcontrollers are widely used for IoT projects like this therefore the choice was obvious.
    - ESP32 boards have a 2.4 GHz radio chip on board which means they support various network protocols based on 802.11 standards – this means it readily supports protocols like Bluetooth and Zigbee.
    - For the purposes of this project the ESP-NOW protocol was used. It's an implementation of 802.11LR which is essentially low power, long-range WiFi. With external antennas, ESP32 can send data over 2 km using this protocol.
    - ESP-NOW has only been implemented as a star network. This means it requires a central gateway node that all the other nodes communicate to. The nodes cannot communicate amongst themselves. It is possible to have separate repeater nodes, but compared to mesh networks, the ESP-NOW setup is not flexible at all, the addresses where nodes send their packets to are entirely preset.
    - The ESP32s were programmed to simply take a reading from the PMS5003 sensor and all the other sensors once every 2 seconds, average them over 60 seconds and then send the average to the

    - gateway. The sampling period of 2 seconds is the fastest sampling that can be set. Setting the sampling rate to be significantly slower (e.g., once a minute) would allow for the fan to be turned off providing significant power saving.
    - The other readings like battery voltage, panel voltage and current, humidity, temperature, are set to occur every 60 seconds. Between the 2 second readings of PMS5003 sensors, the ESP32 was put into light sleep, therefore ESP32 consumed negligible power.
- GNSS (global navigation satellite system) sensor – Quectel L96.
    - A basic GNSS sensor that supports the most popular positioning systems: GPS, GLONASS, BeiDou, Galileo (RLM supported) and QZSS.
    - Was not strictly necessary for this application as the sensors were fixed but being able to locate the sensors if they were moved proved to be beneficial. When deploying sensors, it is possible to simply record the current coordinates manually and then match them with the sensors, but it is much simpler to just rely on the GNSS.
- Heated inlet – series of resistors.
    - During previous research fog and elevated humidity were found to affect the readings of the sensors. This is due to two reasons: firstly, the sensors cannot distinguish between fog and PM as they both scatter the light in a similar way; secondly, there is a hygroscopic effect where PM absorbs moisture from the air and the particles physically become larger inflating the readings. This is one of the main reasons that near-reference sensors like TEOM are operated under specific humidity and temperature conditions.
    - The heated inlets were implemented on some of the sensors during the first deployment but proved to be not necessary. The heaters were activated based on humidity sensor readings recording a humidity level of 80%. The power draw necessary to maintain that level of humidity was justified. Some of the sensor batteries entirely lost power during the first deployment because of the excessive power draw.
- Humidity and temperature sensor – Texas Instruments HDC2010.
    - Just a run of the mill temperature and humidity sensor.
    - ±0.2°C and ±2% RH accuracy.
- Solar panel – 5 V, 10 W, 270 x 270 mm solar panel. Batteries – 4,000 mAh LiPo batteries.
    - This combination was engineered to suit the conditions. Essentially the batteries on their own could power the sensors for just under two full days.
    - During the second deployment when the heaters were not implemented, all the batteries essentially never recorded a voltage under 3.9 V, which correspond to approximately 60-70% state of charge.
    - The second deployment occurred at the beginning of winter with relatively short days, but fortunately only a handful of overcast/rainy days. With the current battery and solar panel setup, it is anticipated that the battery might not be able to maintain the sensors powered if there are 5-7 very dark, overcast days in a row.
- PCB (printed circuit board) – a custom PCB was designed.
    - The main advantage of designing a custom PCB is the ease of assembly and manufacturing.
    - The current PCB includes all the ancillary sensors like the GNSS and humidity/temperature sensors. The PM sensor simply connects using an 8-pin cable and so does the heater.
    - The PCB also features a Micro SD card slot that was not used in this project but could be useful in deployments where no connectivity is available at all or to act as a local data back-up.
    - The PCB has several LEDs that show the state of charge, an LED that flashes when the unit sends a reading to the gateway and another LED that shows whether the sensor is in deep sleep mode or not. Deep sleep mode was activated whenever the unit's battery recorded a voltage below 3.3 V. This was done to prevent the ESP32 from being stuck in the incorrect boot mode which can occur once the battery voltage reduces to below 3.0 V.

    - The PCB also has connections for the solar panel, an ON/OFF switch, connectors for batteries (with battery protection), solar panel current and voltage and battery voltage measuring circuitry.
- Gateway – one ESP32 connected to a Raspberry Pi, powered by a large battery and solar panel.
    - The gateway for the purposes of the implementation is relatively flexible. The only requirement for the gateway is to have an ESP32 connected to a computer that is connected to the internet. The computer can be a laptop, a desktop, a Raspberry Pi, it can also probably be an Android phone (this was not tested).
    - The implementation for this deployment was a large 12 V car battery with a very large 130 W solar panel powering a Raspberry Pi with an LTE modem connecting it to the internet. As the gateway is vital to receiving and sending data from the sensors to the cloud, powering it was probably overengineered. With this set-up, the gateway could function entirely off the battery for at least a few weeks, which could assist with unanticipated relocation due to mining activity.
- Software – different components run different software that will be summarised here.
    - ESP32 runs its own code that was briefly described above.
    - Raspberry Pi's code is based on Node-RED – it simply takes the readings as supplied by ESP32 and sends them off to the Postgres database. The Postgres database is in the cloud running on Linode servers.
    - Linode servers run the Postgres database with the data. The data is then visualised in a Grafana dashboard. Grafana is a very popular data visualisation tool allowing for various plots, diagrams, alerts, notifications, etc.
- Enclosure and mounting
    - The enclosure was designed to contain the PCB, PMS5003 and heated inlet. Additionally, the enclosure also consisted of latching arms for connection to the solar panel, and groove for mounting on site.
    - Enclosure was 3D printed at the University of Newcastle. Additionally, a cover with an insect mesh was also added to combat spiders that were encountered during site deployment.
    - The 3D printed enclosure once latched in place to the solar panel and additional components are shown in Figure 1.
    - Once assembled with all components, the enclosure is simply mounted by hand on top of a star picket, facing north for maximum solar charge.

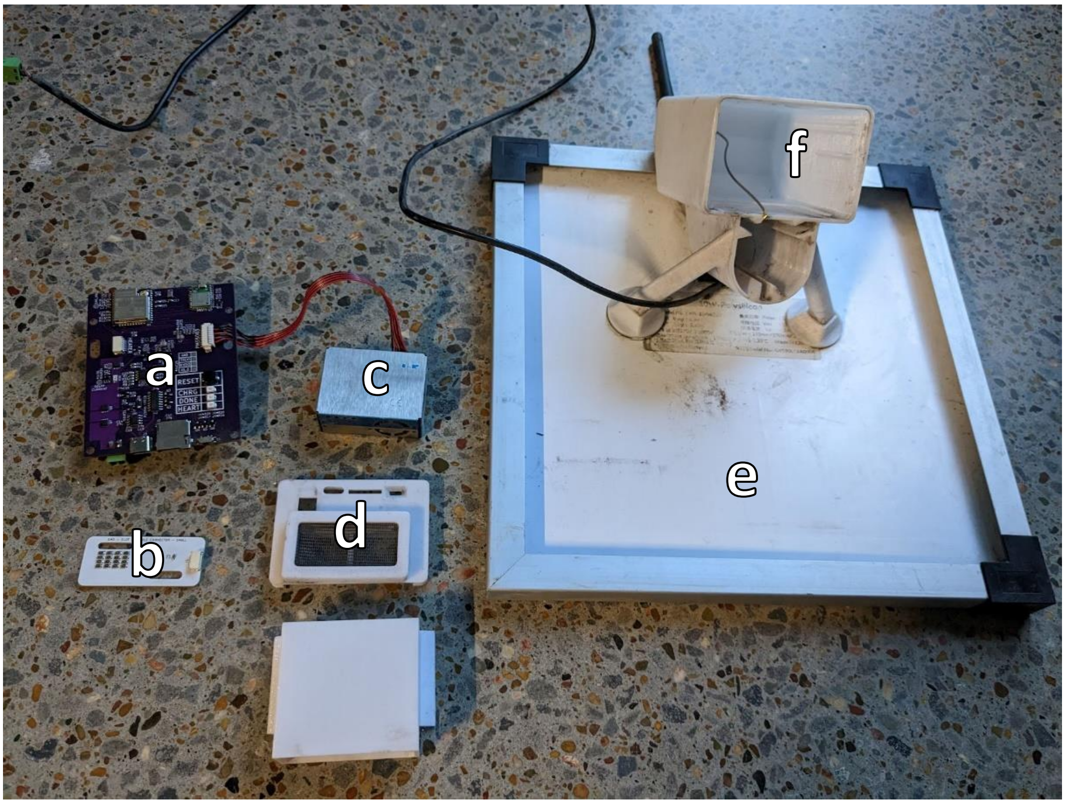

Figure 1: LCS unit with all the main components: a) PCB b) heated inlet c) PMS5003 d) cover with insect mesh e) solar panel f) enclosure with star picket mount

Indoor deployment

In the first instance, the sensors were deployed in an industrial bulk solid and granular materials testing workplace located at the University of Newcastle NIER precinct. Initially nine of these sensors were put next to what were thought to be major dust generating activities such as rotary sample dividers, particle size distribution vibrating machines, dust extinction moisture testing room and adjacent to impact and abrasive wear testers. The sensors were installed, their purpose communicated to the workers as well as the workshop manager. The relatively simple dashboard was set up with a both line plots, as well as a plan of the workshop. The real-time online dashboard, shown in Figure 2was shared with the workers and the workshop manager too.

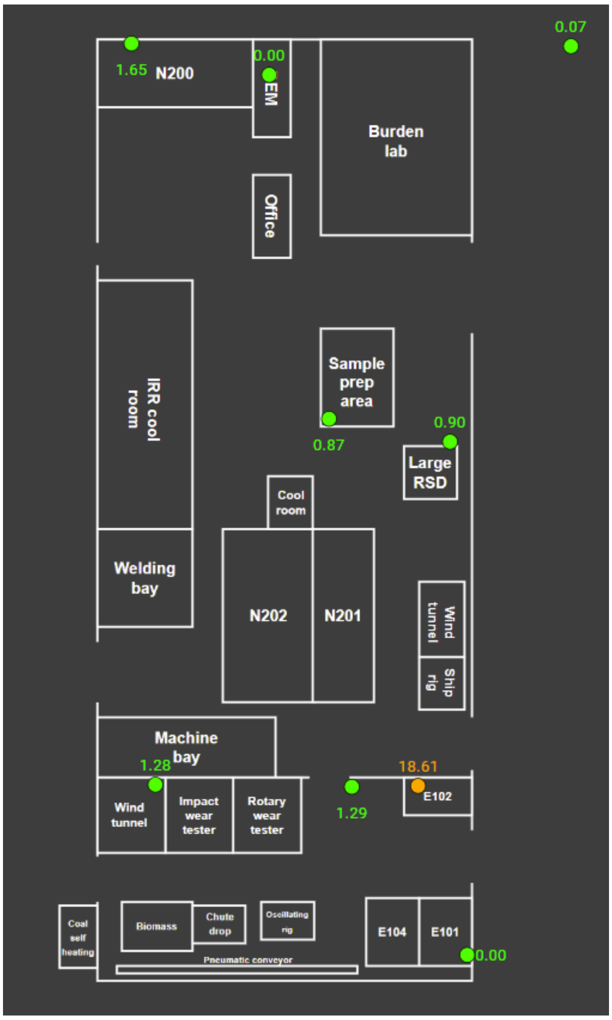

Figure 2: Workshop plan with LCS PM monitors in key locations. This visualisation allows for detecting problematic areas or activities in real time.

Results

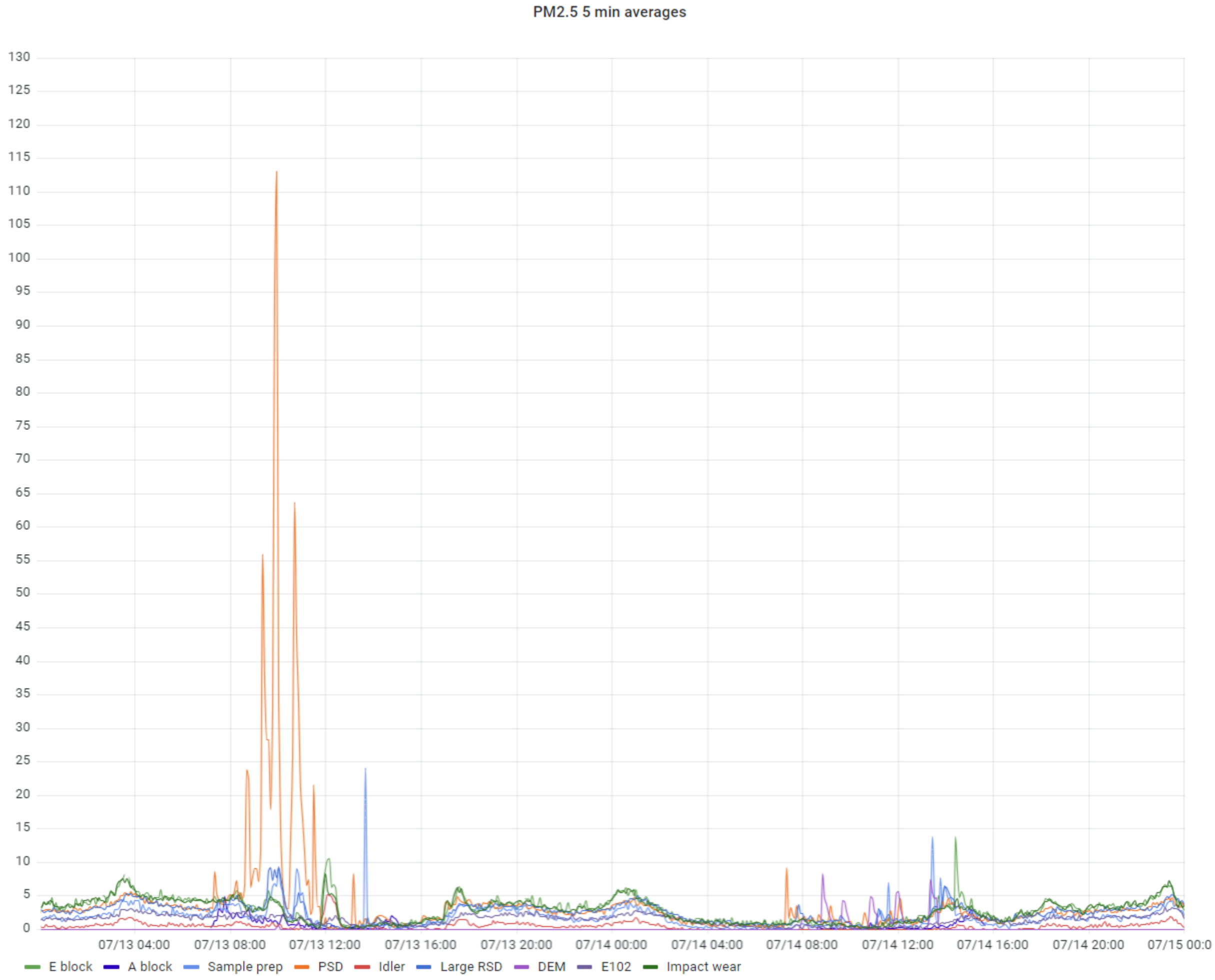

Figure 3: Line-style visualisation of the workshop data. Can track PM levels and assess effectiveness of dust management techniques.

The initial sensor implementation proved very useful for dust management in the workplace. Key areas of dust generation were identified, and extra dust extraction units were installed in those areas. At the end of the trial the dust sensors installed were upgraded to their site-ready versions and taken away from the workshop. Following success of this deployment, the workshop manager replaced the dust monitors with similarly implanted sensors of his own making. The currently implemented sensors work in a similar way, but with the addition of bright coloured LEDs that alert the workers if the dust levels are elevated on a specific sensor or in specific location.

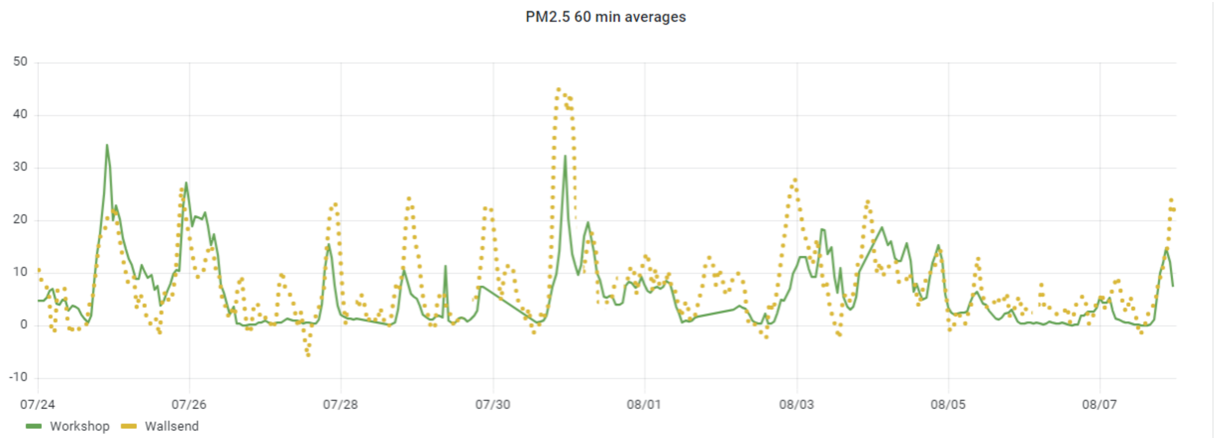

Figure 4: Comparison of low-cost sensor data from the workshop with a nearby government operated monitoring station.

Another aspect that was implemented along with the sensors themselves was visualising the data from the nearby NSW state government monitoring station. The closest one to the University, located around 3 km away in Wallsend showed remarkably similar trends to the monitors installed in the workshop. Since the workshop is not naturally ventilated, most emissions in the workshop may be attributed to the shared Newcastle airshed and not from the activities in the workshop itself.

Outdoor deployment

As the sensors were being trialled in the NIER workplace, the outdoor versions were developed in parallel. Once the indoor trial was concluded, most of the workshop units were converted into outdoor versions of the LCS. The deployments were in two parts – deploying the gateway and the sensor units themselves. The main consideration for both parts was making sure that line of sight between every unit and the gateway is always maintained. Once the location of the gateway was selected, the gateway unit was put on the ground with its solar panel and antennas, illustrated in Figure 5. The gateway deployment took approximately 30 minutes.

Figure 5: one LCS along with the gateway solar panel and the gateway antennas.

The deployment of the sensors themselves involved simply finding a suitable location, driving a star picket into the ground, and sliding the LCS unit over the top of the star picket as the 3D-printed enclosure was specifically designed for that. The deployment of each sensor took only 2-3 minutes to install, plus the time required to find, drive to and park in a suitable location. For both deployments, installing all the sensors took approximately 2-3 hours. Deployment required planning and coordination with site personnel including technical services manager, environmental superintendent, and mine services supervisor, but in essence was seamless, simple, and very efficient. An illustration of a typical LCS unit on a star picket installed on site is shown in Figure 6.

Figure 6: LCS deployed on a high wall.

The first sensor deployment included a total of 16 units of slightly varying configurations and lasted from March 20 until May 9. The second deployment was from May 18 until June 14 and involved 10 identical units with most challenges and problems encountered during the first deployment eliminated. The main problem encountered during the first deployment involved spiders getting inside the PMS5003 sensors themselves, leaving webs over the photodiode causing the sensors to either read zero or the maximum value of around 3000. The other problem was very high-power draw due to the heated inlets causing some of the sensors to completely empty the battery during the night at times.

Results

The main benefit of LCS is being able to monitor and respond to dust emissions in real-time. This is implemented via an online dashboard that shows historic and current data in an interactive way. While we considered using map data that is obtained by the mine site on a regular basis, we opted towards a less resource intensive exercise for now. In the current iteration of the sensor development, the map used for the dashboard visualisation was a 10 x 10 m resolution map sourced from the Copernicus Sentinel-2 mission that can be updated every 10 days provided the area of interest is not covered by clouds.

Some examples of what the dashboards look like are provided in the report, however for the purposes of summarising the data, it will also be done as tables and graphs, averaging over weeks or days. This is to demonstrate that in addition to live real-time monitoring, the LCS monitoring system can be used to identify areas and/or specific mining activities that may potentially lead to increased risk to workers and continuity of operation.

It makes sense to present these examples of data as separate deployments as the locations monitored changed between them. What is more, the first trial deployment experienced a few challenges with insects getting into the sensors themselves, as well as the gateway being moved to a location where the sensors could not maintain line of sight anymore. These issues were resolved eventually, however, that makes the first deployment more of an experimental one where the issues were still being worked through, whilst the second and third ones, whilst not without issues, can be used to make some conclusions more readily.

First deployment

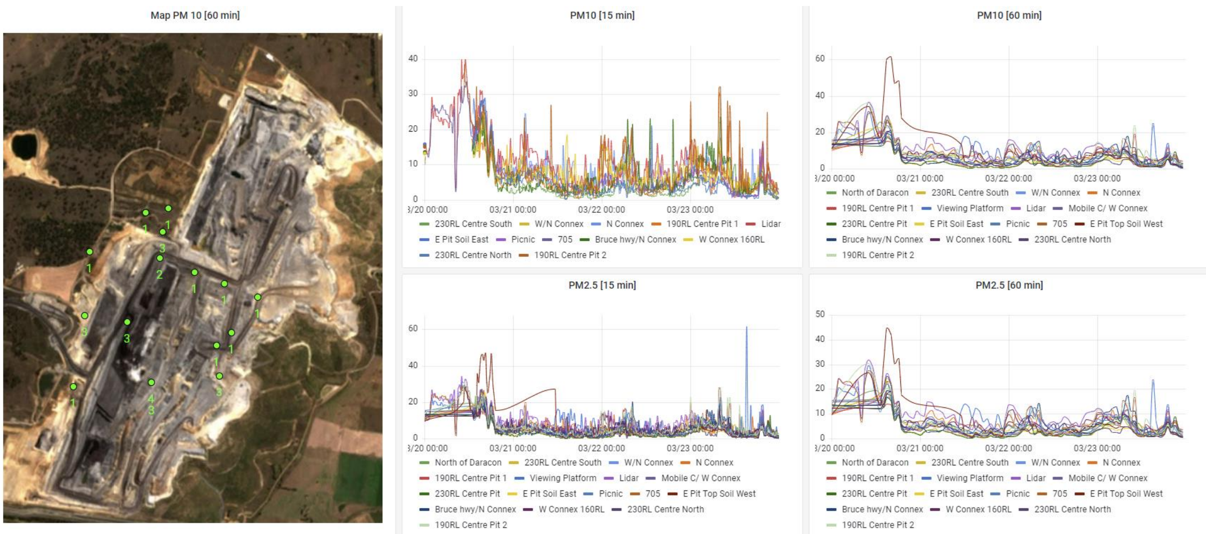

Figure 7: live dashboard view of first deployment.

The data from the first deployment that lasted for six and a half weeks can be looked at in several ways. All sensors showed reliable data in the week, then several sensors started experiencing the challenges mentioned previously, caused by the dynamic nature of an active mine site. Nevertheless, seven sensors remained fully active and maintained line of sight of the gateway for the duration apart from being inactive for all of week six.

Table 1: First deployment PM_{10} weekly averages (μg/m³). Shading highlights sensors that were reliable throughout the deployment.

Location	Week							Average
	1	2	3	4	5	6	7	
North of Darco	8.3	10.8	8.8	NA	NA	NA	NA	9.0
230 RL centre South	4.7	NA	1.6	NA	NA	NA	7.4	4.7
Corner West and North Connex	7.8	9.7	6.4	6.1	11.5	NA	11.2	7.9
North Connex	9.9	12.5	9.1	7.8	8.8	NA	10.6	9.3
190 RL centre pit	6.7	NA	NA	NA	NA	NA	11.6	7.7
Viewing platform	7.1	NA	NA	NA	NA	NA	NA	7.1
LDR	11.9	11.7	69.7	139.4	36.7	9.5	7.5	45.9
Mobile CH, West Connex	6.6	10.5	NA	NA	NA	NA	NA	7.6
230 RL centre pit	3.9	NA	NA	NA	NA	NA	NA	3.9
E pit soil East	5.6	NA	NA	NA	NA	NA	NA	5.6
Picnic	8.8	9.2	5.7	3.7	10.3	9.8	14.8	7.9
E pit topsoil	8.2	6.8	10.2	9.0	15.9	NA	12.4	9.9
Corner North Connex and Bruce Hwy	6.6	11.0	7.7	7.2	9.5	NA	12.6	8.3
Corner West Connex and 160 RL	9.0	8.3	7.0	8.8	17.5	NA	11.8	9.3
230 RL centre North	5.6	3.3	NA	NA	NA	NA	NA	5.5
190 RL centre pit	7.5	NA	21.9	NA	NA	NA	11.9	9.2

Table 1 summarises the first deployment results. Considering this is an active mine site, all the locations show consistent and generally low readings apart from the LDR lookout linked to significant earthworks and subsequent preparation for that area to be blasted. Other than that, the averaged data can suggest that, for example, locations next to the high trafficked areas adjacent to haul roads (e.g., sensors at Corner West and North Connex and Corner North Connex and Bruce Hwy) showed higher dust generation during week 2 and week 5 compared to week 1 and week 4 respectively, suggesting that dust suppression at those particular locations was not as effective during that time for the conditions and handled materials properties at hand. This type of information illustrates how integrating the LCS into dust management could indeed reduce dust levels – for example if higher dust measurement values are being recorded over a period of time a higher level or more frequent dust mitigation action could be implemented.

Second deployment

Initial sensors and gateway were collected from site, the challenges identified during the first deployment fixed and the sensors were redeployed under two weeks later, on May 18. There was a temporary issue with gateway connectivity on site that was resolved on May 25 and all ten LCS worked reliably after that. The data can be summarised both in a plot and a table for easy comparison as shown in Figure 8, Figure 9 and Table 2.

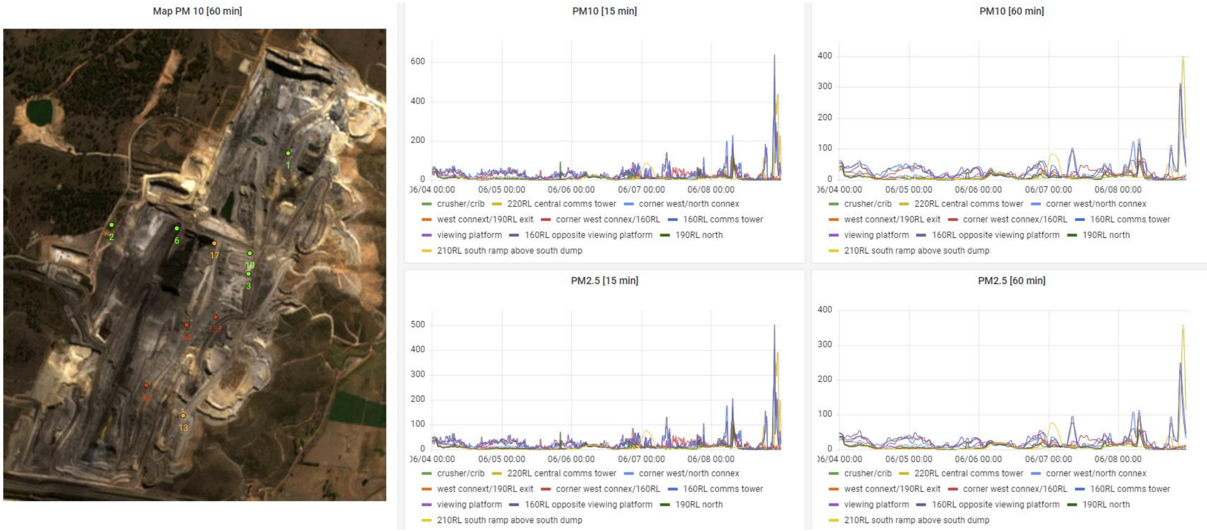

Figure 8: live dashboard view of second deployment.

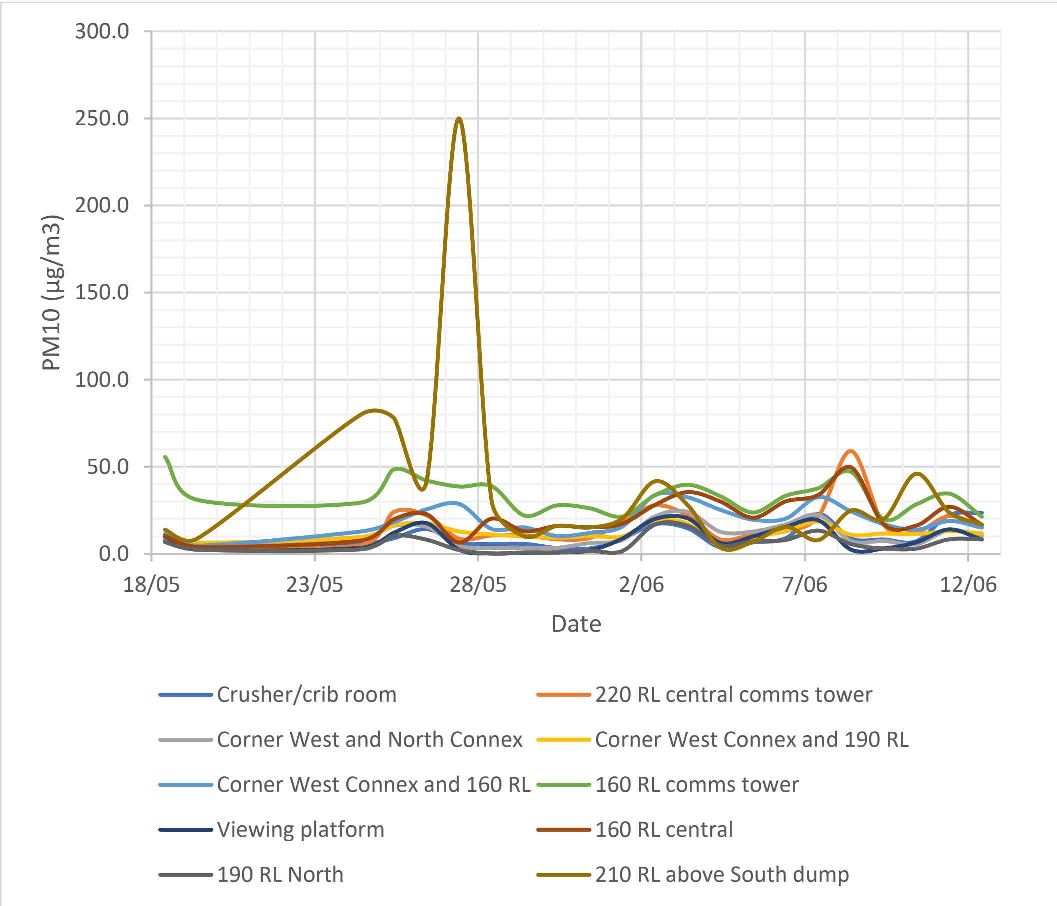

Figure 9: Second deployment PM_{10} daily averages.

Table 2: Second deployment PM_{10} daily averages (µg/m^3). Shading highlights areas of elevated concentration

Date	Crusher/crib room	220 RL central comms tower	Corner West and North Connex	Corner West Connex and 190 RL	Corner West Connex and 160 RL	160 RL comms tower	Viewing platform	160 RL central	190 RL North	210 RL above South dump
18/05	7.9	9.3	10.4	11.5	11.3	55.6	10.0	10.3	6.7	13.8
19/05	3.0	4.1	3.7	6.4	4.7	30.9	2.4	4.0	2.3	8.9
24/05	5.4	4.9	9.1	9.6	12.8	29.4	3.4	7.6	2.6	80.0
25/05	9.0	24.0	16.1	16.4	18.2	48.4	12.1	19.8	10.4	78.0
26/05	14.2	22.1	15.5	17.6	25.5	42.1	17.6	22.7	8.1	41.4
27/05	6.4	8.7	4.5	12.8	28.6	38.6	2.3	6.4	2.2	250.0
28/05	5.7	10.5	3.4	11.1	14.2	38.8	0.2	20.2	0.2	30.0
29/05	5.7	10.5	3.4	9.9	15.1	21.9	0.6	12.9	0.8	10.0
30/05	3.3	8.3	3.4	9.2	10.2	27.8	0.8	16.0	0.8	16.0
31/05	3.1	9.1	6.2	10.2	12.0	26.1	1.9	15.2	1.7	15.1
1/06	8.5	18.0	7.9	10.0	15.7	21.4	8.8	17.3	1.6	20.3
2/06	17.1	27.8	21.5	19.3	33.8	33.6	20.0	28.1	16.8	41.6
3/06	14.6	22.0	24.1	17.2	32.4	39.6	20.3	35.4	16.0	27.9
4/06	3.7	8.2	12.6	4.6	25.2	33.0	6.2	30.0	4.9	3.5
5/06	6.5	11.1	12.8	9.2	19.6	23.7	9.9	20.7	7.2	6.9
6/06	8.9	13.0	16.9	13.2	20.2	33.3	15.5	30.1	8.0	15.5
7/06	22.9	21.6	22.3	18.5	32.6	37.7	19.2	33.8	13.3	7.9
8/06	8.8	59.0	7.2	10.9	24.3	47.0	2.4	49.6	5.6	24.8
9/06	8.2	16.6	7.4	11.6	17.0	19.8	3.1	16.9	3.0	20.0
10/06	7.2	12.6	5.5	11.3	13.8	28.4	6.6	16.2	3.0	46.0
11/06	22.2	21.7	13.5	13.0	18.8	34.5	14.0	27.0	8.3	23.8
12/06	23.5	15.3	10.3	11.7	15.0	21.3	8.2	16.7	8.4	16.8
Average	9.8	16.3	10.8	12.1	19.1	33.3	8.4	20.8	6.0	36.3

Once again, the data demonstrates the intended main purpose of LCS units is to use them as early warning, real-time tools to help with dust management and workplace exposure. However, even using them in this retrospective way demonstrates that they can be used as actual tools to improve environmental and worker health and safety. For example, specific areas of increased dust generating activity could be identified and anticipated, thus alerting workers through weekly mine planning communication thereby acting to prevent incidence that may lead to unsafe exposure. This is relevant to workers outside cabins, which may include those working on heavy machinery in specific locations around the site. Once again, the sensors located nearby haul roads show elevated PM values but only on certain days. What is more, the two sensors highlighted in Table 2 were both located towards the East side of the site and can be linked to significant dumping activities in that area. Once again, this proves the usefulness of LCS in identifying areas of the mine site that have increased dust emission levels. With additional site data such as heavy machinery, water cart locations and meteorological conditions, this data can be used to either target the specific dust generating activity or adjacent activities where mine workers outside of cabs may be present.

Targeting specific areas

After having the sensors deployed in and around the pit for relatively long-term deployments, a few sensors were then re-deployed for two relatively short-term deployments, targeting two different areas where workers outside of cabins could potentially be affected by dust coming from adjoining activities. The areas for investigation were selected in collaboration with mine staff personnel, that now also included the site hygiene and health team. Specifically, an active drill pattern and build-pad areas were selected.

The first location was workers setting explosives in preparation for blasting. Four sensors were deployed around the drill pattern as the explosives were being put in. In this case, the only adjoining activities that would generate dust were haul trucks a few hundred meters away. For this campaign, all sensors and the gateway were first reclaimed from site, with four sensors and the gateway without the solar panel then re-deployed in the drill pattern area immediately thereafter. This process took 1-2 hours, thus the sensors were active in this area for approximately four hours The sensors were deployed at four locations at the corners of the drill pattern, on the bunds. During the four hours of monitoring the dust in this location, the dust levels on all four monitors remained under 1.0 µg/m^3. This specific day was also fairly damp and overcast, with the sun only appearing for the photo below in Figure 10.

Figure 10: LCS around the perimeter of drill pattern area.

On the same day, after monitoring the drill pattern activities, the sensors and gateway were then moved to another area of the mine as the first area was scheduled to be blasted the following day. The other area was a build-pad directly above an actively mined area. The build-pad included maintenance, a crib room and some other facilities as shown in Figure 11 to Figure 14. Also shown in Figure 13 and Figure 14 is the location of the sensors, while Figure 15 shows the data obtained.

Figure 11: build-pad location, LCS 805 for targeted deployment.

Figure 12: build-pad LCS overlooking actively mined area.

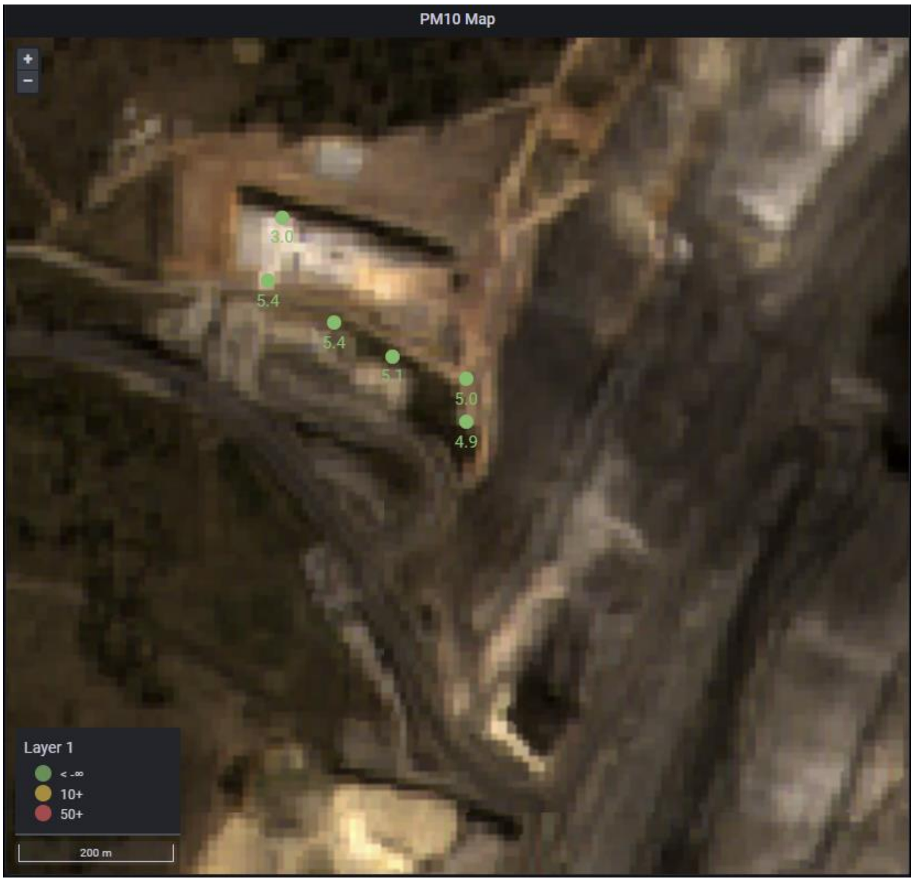

Figure 13: real-time map of build-pad location monitoring. Locations provided by the GPS inside the sensors themselves.

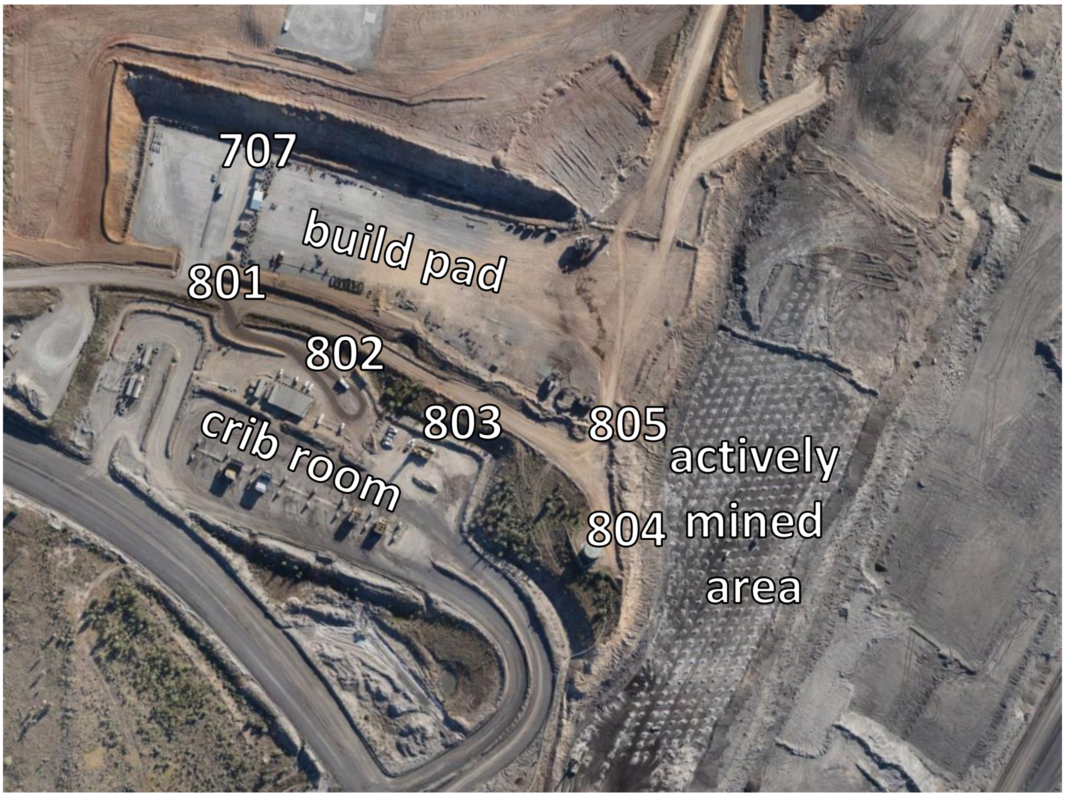

Figure 14: build-pad location map showing key locations. Numbers indicate approximate sensor locations.

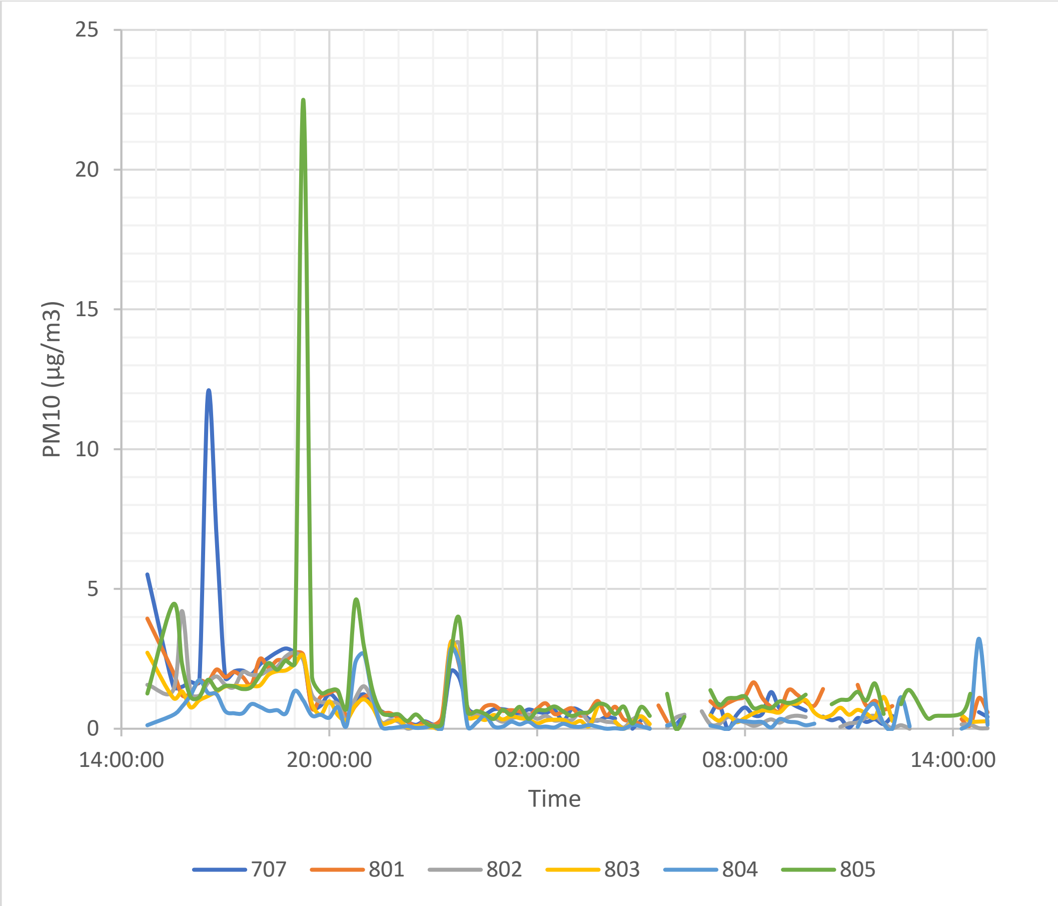

Figure 15: PM_{10} from targeted deployment at build-pad.

Once again, during the monitoring period, in general, the emission levels remained relatively low. Four distinct events or peaks can be identified. One originating at the sensor 707 that was located near a parking area. The other three peaks likely propagated from the actual mining area, which is evidenced by the peaks first appearing on sensor 804 and 805, which were located closest to the bund in sight of the actual mining area. Nevertheless, the actual PM levels remained low throughout.

Accuracy assessment

Co-location setup

As part of the project, six LCS units were located at one of the regulatory monitoring stations operated at the boundary of the mine site. The mine site monitoring station is comprised of a gravimetric method (a HiVol) as well as a real-time PM monitor (MSM-2). MSM-2 is a near-reference monitor that is based on the light scattering technology that the LCS use, however, compared to the LCS, the MSM-2 has passed the AS 3580.9.17:2018 equivalency checks that will be discussed further in this section. In addition to the PM monitors, the mine site monitoring station housed a full weather station, providing wind speed, direction, temperatures, relative humidity, solar radiation, and rainfall measurement all with 5 minutes resolution. The mine site granted the authors of this report access to the dashboard that provides both live and historic data from this station.

Figure 16: Mine site monitoring station – six LCS next to HiVol (reference) and MSM-2 (near-reference) methods.

A total of six LCS were located within proximity to the monitors the mine site uses for regulatory compliance as shown in Figure 16. Three of the sensors were the versions that were used for the actual site deployment and the other three were the same version as used in the NIER workshop. This was done to make sure that their unintended differences were not introduced to the site monitoring campaigns as the technology and method transitioned from indoor to outdoor implementation. The mine site monitoring station assessed is located close to the two stations operated by the NSW state government. The state government monitoring stations are located approximately 1.2 (NSW-1) and 1.8 km away (NSW-2).

AS 3580.9.17:2018 procedure

It is important to briefly describe AS 3580.9.17:2018, mainly its purpose and why it is used for this comparison. AS 3580.9.17:2018 is called *Method for sampling and analysis of ambient air. Method 9.17: Demonstration of equivalence for ambient particulate matter monitoring methods.* The main purpose of the standard is to outline a procedure to check whether a new PM monitor is accurate enough to be used for regulatory compliance. The comparison is made with a reference method – in the space of PM measurement, the reference is always a gravimetric method, i.e., a device that directly collects the PM on a filter that is then weighed using an extremely accurate and precise scale. Any monitor that passes the checks outlined in this standard can then be called a near-reference or equivalent (to the reference).

The outline of the standard here will not be very detailed in the interest of not repeating what the standard itself already says. Only the key points are discussed. This Australian standard relies on US EPA guidance but is mainly based on the European *Guide to the Demonstration of Equivalence of Ambient Air Monitoring Methods* (EC Guide) released in 2010 as well as the European standard EN 15267. All the equivalency calculations done in AS 3580.9.17:2018 are identical to those in the EC Guide. The way US EPA determines equivalency is similar in procedure, but the calculations are very different.

Overall, to pass the Australian equivalency standard, a PM monitor needs to fulfill certain requirements. They are outlined below:

- The monitors under consideration (also called candidate methods or CM) need to be already on the list approved by US EPA (https://www.epa.gov/amtic/air-monitoring-methods-criteria-pollutants) or have passed EN 15267. In Europe, the monitors are tested and certified by TÜV Rheinland in Germany (https://qal1.de/en/systeme2.htm) and CSA Group in the UK (https://www.csagroup.org/en-gb/services/mcerts/mcerts-product-certification/mcerts-certified-products/mcerts-certified-products-continuous-ambient-air-monitoring-system/). One of the important steps of getting designated as an equivalent method in either the US or Europe is passing manufacturing quality controls, i.e., satisfying the certifying body that manufacturing of the monitors is done in an extremely consistent way and to a high quality.
- Once a monitor is certified in the US or Europe, it can then be assessed in Australia using AS 3580.9.17:2018. This assessment must be done at five different sites that are representative of the conditions the monitors are intended to be used. This is both in terms of composition of the PM and climate – the standard provides a map of Australian climate zones and equivalency can only be claimed for a certain climate zone.
- Only the between monitor uncertainty (the standard uses the term uncertainty, but the for the purposes of this discussion and can be understood as error) is to be measured and calculated at all five sites. The actual equivalency can be assessed at one site, but at least two comparisons need to be made.
- A comparison can be done once 40 daily data pairs are obtained. A data pair is essentially a 24 h average captured by both the reference and candidate method. A minimum of 95% data capture is considered valid. At least two candidate methods are compared to at least one reference. With more than one method used, their results are averaged.
- The comparison is allowed to be calibrated, i.e., the candidate method results can be scaled and offset. But obviously for the purposes of AS 3580.9.17:2018 only one calibration is allowed, i.e., it cannot be varied for day by day.
- The calculations are not very complex and boil down to two numbers:
    - Between instrument uncertainty that must be below 2.5 $\mu g/m^3$

        - Note that reference methods have their own between instrument uncertainty, but the standard allows 1.0 µg/m³ to be assumed).
    - Combined relative uncertainty that must be below 25%.
        - A crucial detail of the combined uncertainty is that it is calculated as a function of PM concentration, i.e., uncertainty varies with concentration and if there are few readings at that concentration, the uncertainty calculated will be relatively high.
        - For the purposes of regulatory compliance, it makes sense to use the PM concentration stated in the regulatory conditions of the licence under which the mine site operates.

If both conditions are satisfied (along with all the prerequisites in the preceding bullet-points), the monitors can be considered equivalent to the reference.

Between instrument uncertainty

The equivalency comparison will be done over a period of approximately 60 days between 20/03 and 18/05. This is the longest completely uninterrupted period of the MSM-2 sensors reporting basically 100% of the data. There were some interruptions before and after those dates due to issues with internet connectivity. Figure 17 only shows five sensors. The LCS unit D was affected by an insect, so for a long period of time it was saturated, i.e., reporting data above 3000 µg/m³. Nevertheless, Figure 17 shows almost perfect agreement between the sensors with the only significant difference being the LCS unit C which showed some higher values compared to the other sensors on a few occasions (the sharp peak on 07/05 is likely related to an insect as the sensor was saturated for a few hours).

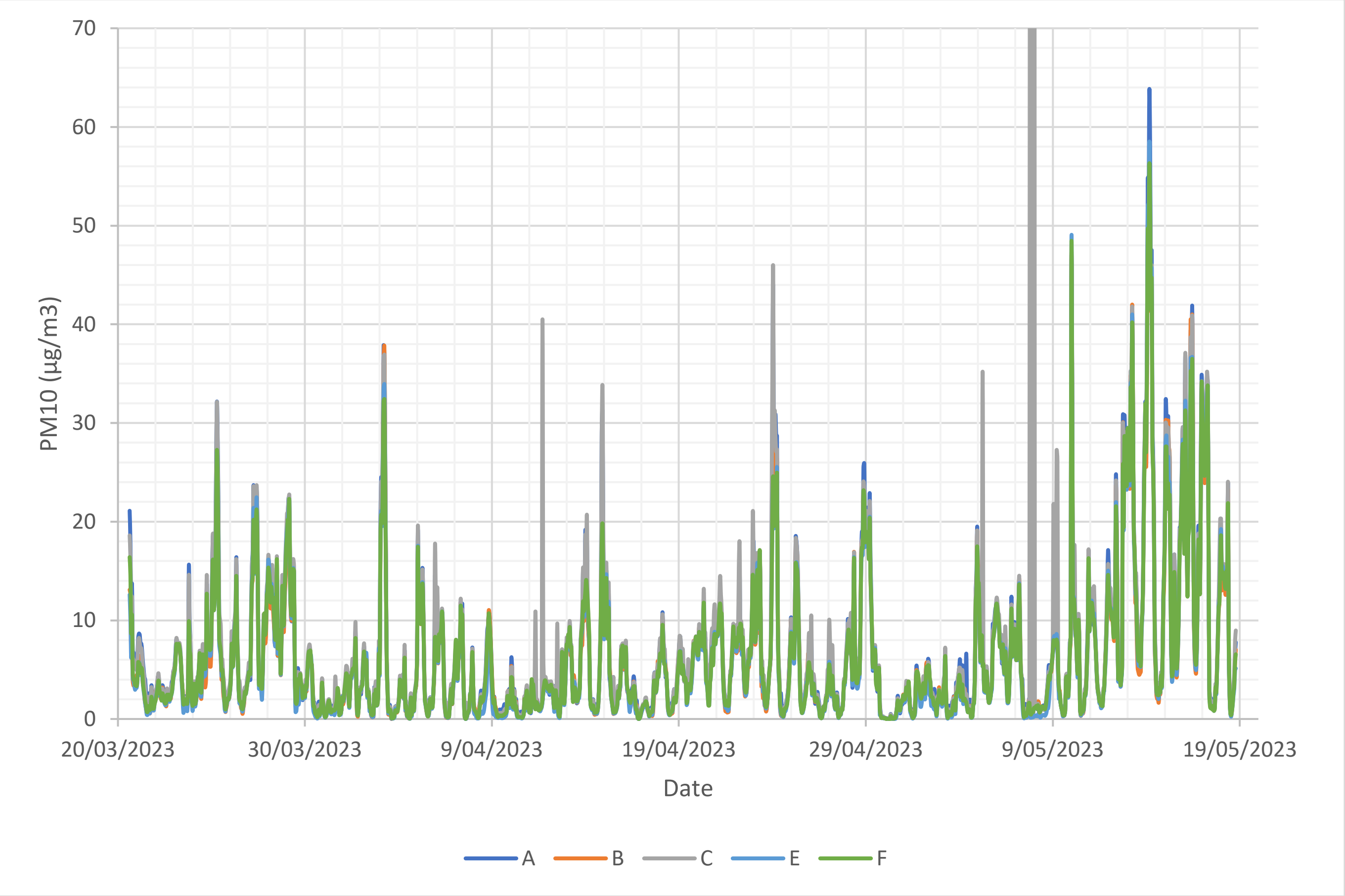

Figure 17: LCS situated at MSM-2. Hourly PM_{10} data.

According to AS 3580.9.17:2018, the between instrument uncertainty is calculated between pairs of sensors. It therefore makes sense to present these uncertainties as a table. This comparison can be made both on a daily and hourly basis. Table 3 presents the pair-wise uncertainties with all days included and Table 4 is the same table, but with 07/05 excluded from the results for all the sensors as LCS unit C was affected by an insect on that day. The comparison can also be done using hourly data – this can be done to illustrate that doing this kind of comparisons using smaller time intervals increases the uncertainty. Table 5 shows the uncertainties using hourly LCS data but also excluding seven hours for all sensors when LCS unit C data was saturated.

Table 3: between instrument uncertainty based on daily PM_{10} data.

	A	B	C	D	E
A	0.00	0.86	42.58	1.02	0.87
B	0.86	0.00	42.60	0.47	0.34
C	42.58	42.60	0.00	42.71	42.63
D	1.02	0.47	42.71	0.00	0.33
E	0.87	0.34	42.63	0.33	0.00

Table 4: between instrument uncertainty based on daily PM10 data excluding the 07/05 for all monitors.

	A	B	C	D	E
A	0.00	0.86	0.58	1.02	0.88
B	0.86	0.00	1.09	0.46	0.34
C	0.58	1.09	0.00	1.26	1.10
D	1.02	0.46	1.26	0.00	0.32
E	0.88	0.34	1.10	0.32	0.00

From the tables above, clearly all pairs of sensors satisfy the between instrument uncertainty criteria of AS 3580.9.17:2018, i.e., all of them are below 2.5 $\mu g/m^3$. This is consistent with all the observations in the literature where the vast majority of authors report very low variability among PMS5003 sensors. This low variability is precisely the reason that allows these sensors to be used for qualitative/comparative assessments such as ones described in this report.

Table 5: between instrument uncertainty based on hourly PM10 data excluding seven hours on 07/05 for all monitors.

	A	B	C	D	E
A	0.00	1.23	1.75	1.55	1.45
B	1.23	0.00	2.09	0.84	0.81
C	1.75	2.09	0.00	2.29	2.22
D	1.55	0.84	2.29	0.00	0.55
E	1.45	0.81	2.22	0.55	0.00

Expanded relative uncertainty

The calculation for the expanded relative uncertainty is a little bit more complicated compared to the single equation of between instrument uncertainty. This calculation was done in Matlab and to make sure that the calculation was done correctly, it was first performed on an example data set provided in the standard itself. NB: the calculation steps in the AS 3580.9.17:2018 contain an error – step C4 in Appendix C, calculating S_{xy} squares the terms whereas they are not meant to be squared. Annex B of the EC Guide contains the correct calculation which is used in the following analysis.

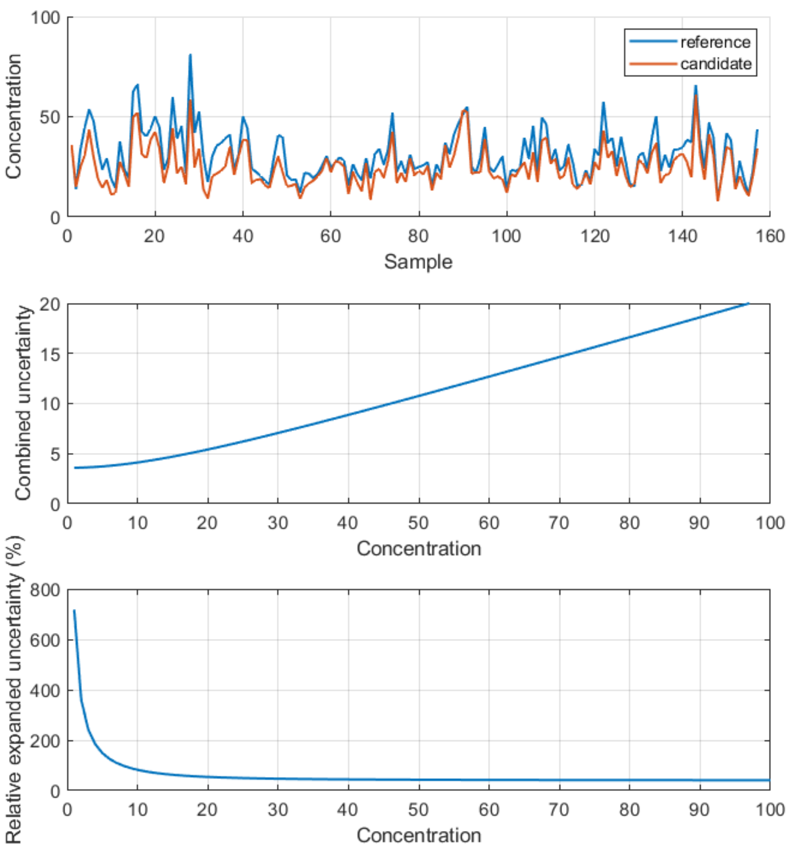

Figure 18: AS 3580.9.17:2018 example calculation.

Figure 18 presents the example calculation using example data. The result of the calculation is that the candidate method fails the assessment because the expanded relative uncertainty is approximately 43% at 50 µg/m^3. Note that this is even though the actual data comparison between the reference and candidate does correlate well. In the example data set, the data is then calibrated by changing the slope and offset, following which uncertainty of 18.4% is achieved satisfying the standard's criteria.

Applying the same calculation comparing daily data from the MSM-2 to the average of the four LCS units (excluding both C and D units for simplicity – both had issues with saturated measurements most probably due to insect infiltration). The resulting expanded uncertainty for the LCS ends up being 84% for daily and 129% for hourly data. Note how both Figure 19 and Figure 20 have significant discrepancies between the MSM-2 (reference) and the LCS (candidate).

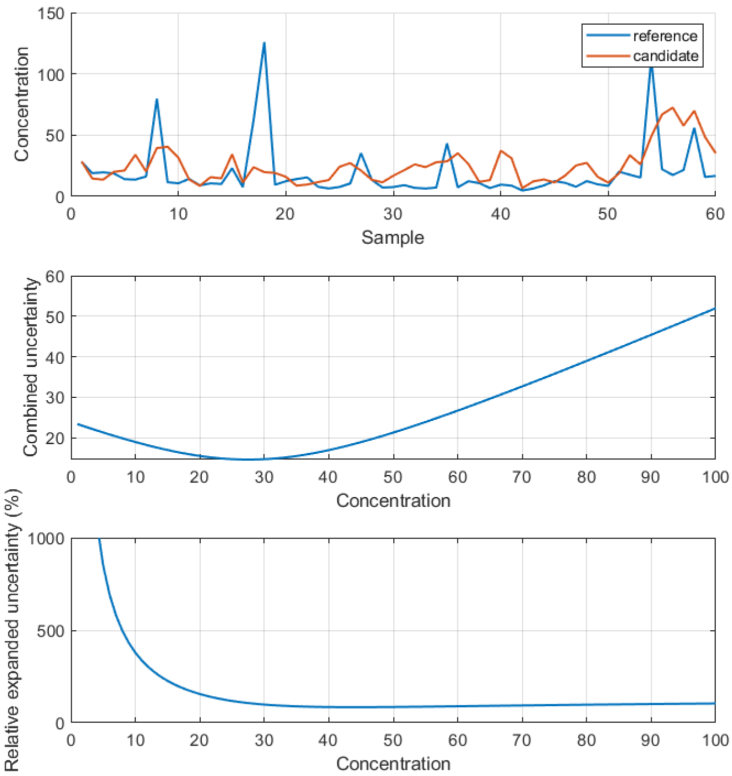

Figure 19: AS 3580.9.17:2018 calculation using daily MSM-2 data.

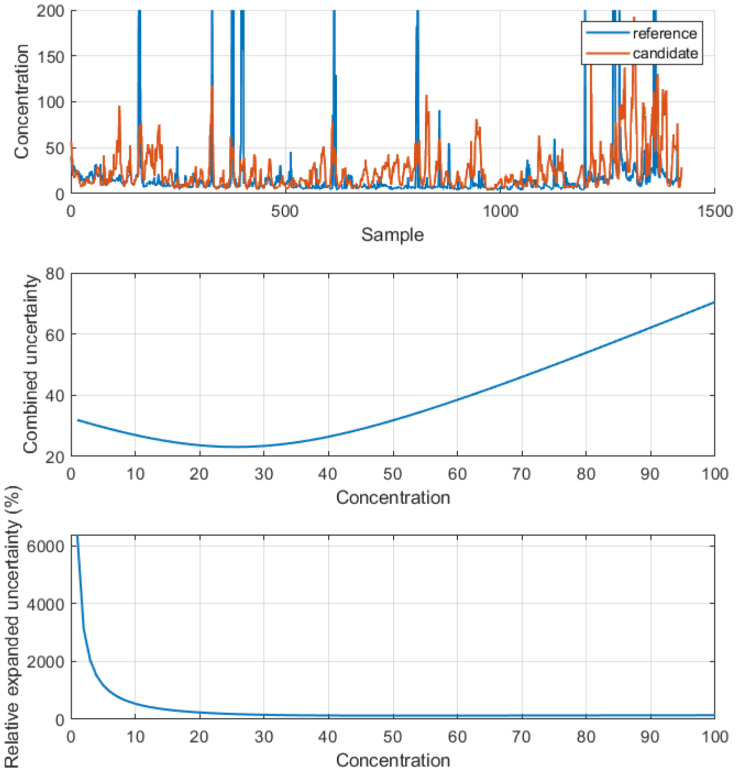

Figure 20: AS 3580.9.17:2018 calculation using hourly MSM-2 data.

The discrepancies between LCS and the MSM-2 instrument can be assessed in more detail. It is best to examine them on a weekly basis. Figure 21 and Figure 22 show PM_{10} values for week number 1 and 3 of comparison period and include data from MSM-4 and MSM-5 which are approximately 3 km North-East and North-West from the mine site as well as an additional NSW state government monitoring station (NSW-3) located approximately 4 km West of the mine site.

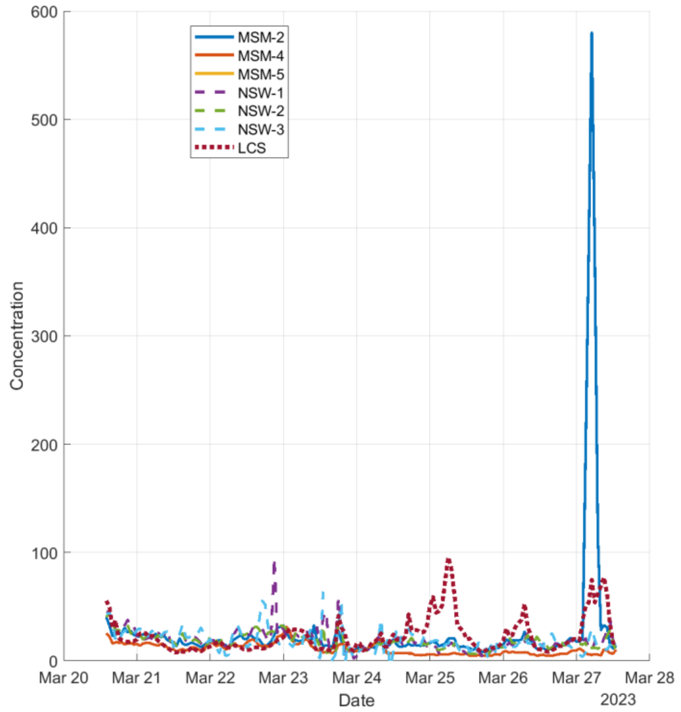

Figure 21: week 1 PM_{10} readings of LCS, mine site monitors and NSW government stations.

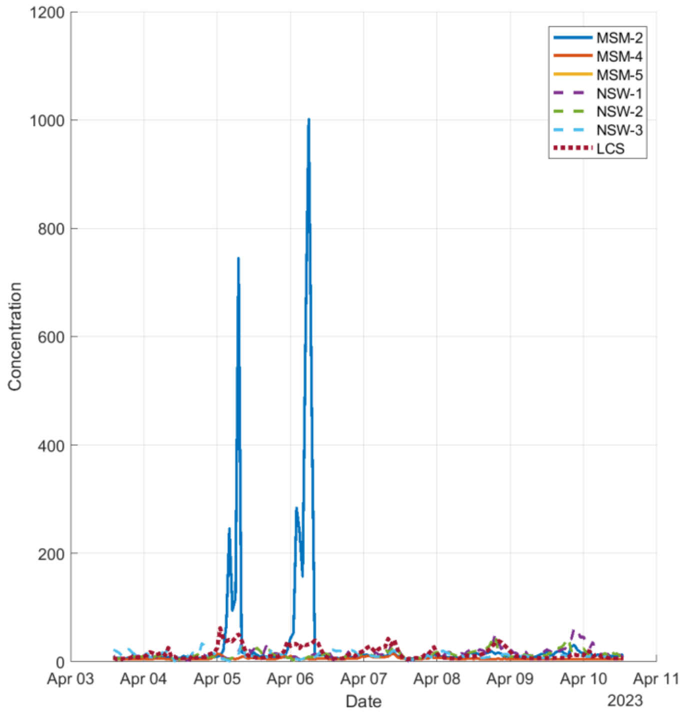

Figure 22: week 3 PM_{10} readings of LCS, mine site monitors and NSW government stations.

The comparison clearly shows that the MSM-2 instrument registers very high PM levels when none of the other instruments show levels anywhere near that. Bear in mind, that the levels registered by MSM-2 are very high and if they were real events, they are likely to have caused at least some response at one of the nearby state government monitoring stations. In other words, it is highly unlikely that a PM10 concentration of a 1000 µg/m^3 did not register as higher than at least 20 μg/m^3 at one of the other monitoring stations. What is interesting, is that the vast majority of these high PM events registered only by the MSM-2 occurred early in the morning, usually between 03:00 and 08:00 – Figure 23 demonstrates this.

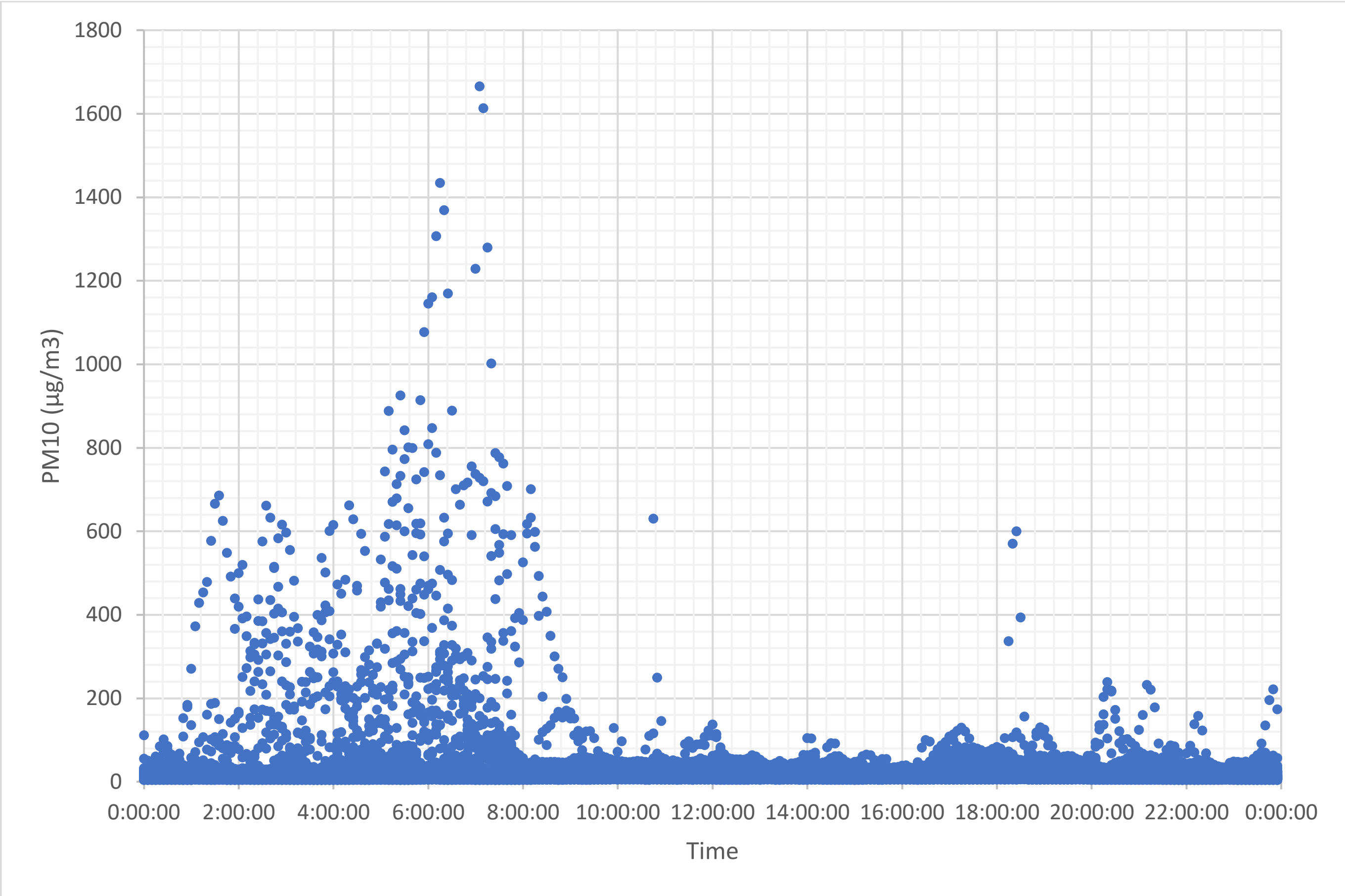

Figure 23: MSM-2 PM10$_{10}$ readings as a function of time – average over the assessment period.

What is more, almost all these extremely high readings occur when humidity is above 90% (see Figure 24). MSM-2 is based on light scattering technology that is susceptible to reading fog as particulate matter, but this should not be the case as MSM-2 has a heated inlet and the LCS did not get affected by these fog events. The authors of this report have encountered the fog problem with the LCS personally in previous research, and it is highly unlikely that the fog affected only the MSM-2 and not the LCS. Furthermore, on many of the mornings with high humidity when these readings occurred, the temperature was relatively high, making fog unlikely.

In any case, the aforementioned factors do not necessarily suggest that MSM-2 provided erroneous readings, but the uncertainties calculated in this section were done with comparison to an instrument that itself has errors (albeit small enough to be considered equivalent).

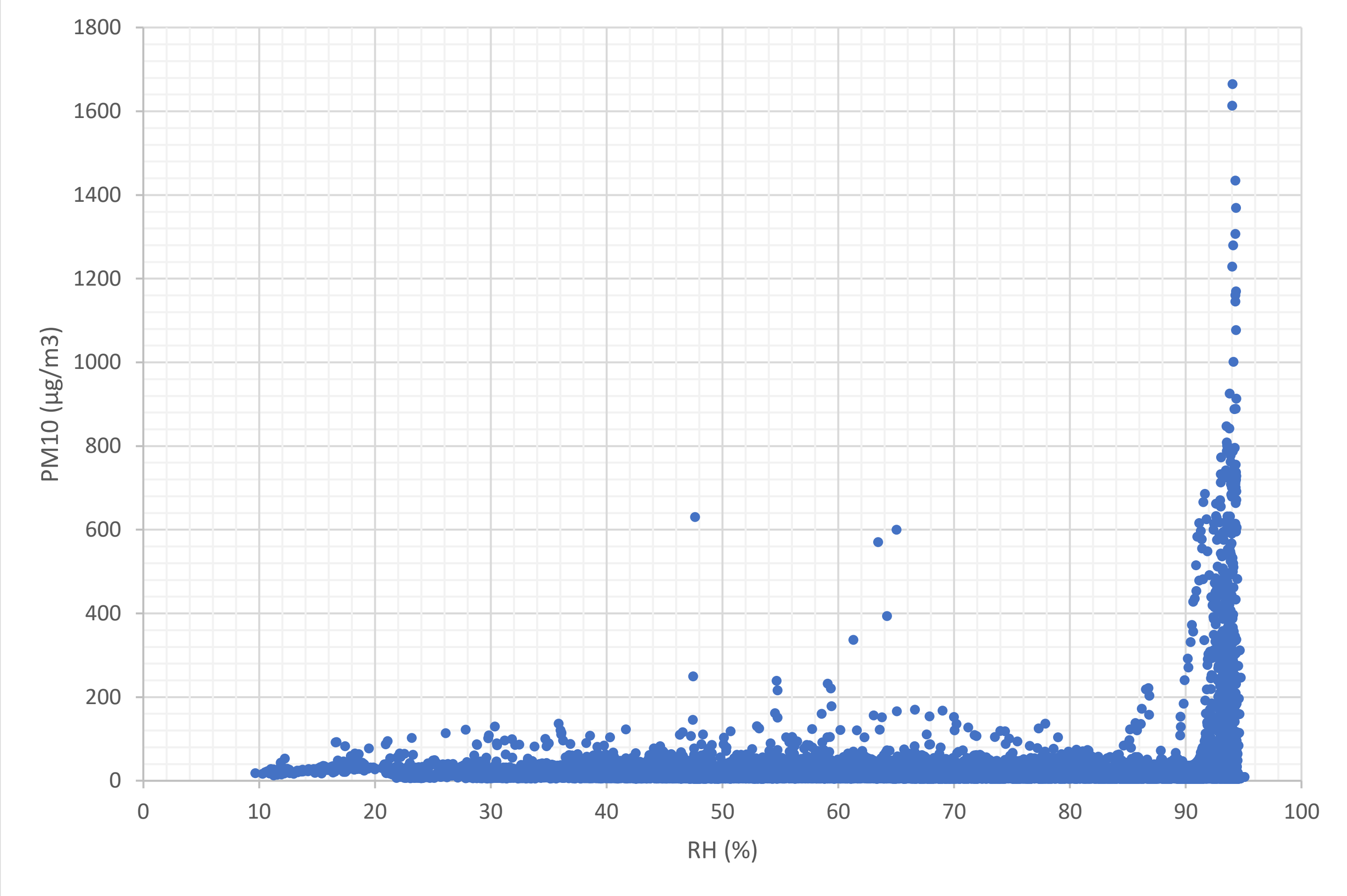

Figure 24: MSM-2 PM10 readings as a function of relative humidity.

Conclusion

This project has demonstrated that purpose built low cost particulate matter sensors (LCS) can be used to inform both environmental and occupational health dust monitoring on a mine site. As part of the project, a number of custom sensor units were built and trialled. At first, the trial included a deployment in an indoor workplace handling bulk materials. The indoor trial resulted in the dust sensors being integrated into dust management permanently by the workshop manager. After the indoor trial, the outdoor variant of the units was developed, built and deployed on an open cut mine site in different campaigns. Key findings from our project are:

- LCS as used for this project cost approximately $100-150 in parts. The sensors provide 1 minute averages that can be visualised in real time on a dashboard.
- The sensors can be installed in long term deployments targetting environmental monitoring – for example, monitoring multiple locations scattered across a site to identify areas that produce more dust than others. This can lead to the identification of specific mining activities that are contributing to increased dust generation, thus triggering a specific mitigating action response.
- The sensors can also be employed for occupational workplace health monitoring such as surrounding an area with workers outside of cabins in order to investigate if these workers are exposed to dust generated by an adjoining activity. This can lead to the identification of specific simlar exposure groups of workers that may be exposed to increased dust generation, thus enabling improved prevention measures to reduce or eliminate exposure.
- A full deployment of ten sensors takes approximately 2-3 hours with majority of the time spent driving between the locations. Actual deployment of a single sensor takes only 2-3 minutes.
- Low-cost dust monitors trialled have an expanded relative uncertainty of 84% when compared to a reference monitor instrument over 60 days at a concentration equal to that under which the mine site operates.