AN INVESTIGATION INTO THE USE OF LIGHT DETECTION AND RANGING (LIDAR) FOR OPERATIONAL DUST CONTROL AT OPEN-CUT COAL MINING OPERATIONS

Damon Roddis[1], Liza McDonough[1], Ashley Martin[1], Yunhui Zheng[2];

[1] Pacific Environment, 146 Arthur Street, North Sydney NSW 2060

[2] Sigma Space Corporation, 4600 Forbes Blvd, Lanham, MD 20706, USA

Abstract

Pacific Environment was awarded grant C52029 from the Australian Coal Association Research Program (ACARP) to investigate the use of lidar (Light Detection and Ranging) for operational dust control at open-cut coal mining operations.

The objective of this work was to investigate suitable options and implement a real-time monitoring method that would provide accurate detection of particulate matter (PM) movement across significant and critical sections of a site boundary, with the potential to be visualised in real-time.

Such a demonstration could assist the mining industry by providing early detection of adverse PM movements across site boundaries. Real-time information will enable the industry to better manage on-site dust emissions, reduce unnecessary production stoppages and improve general air quality in the area.

Field measurements at the Hunter Valley Operations (HVO) mine identified dust emissions from blasting, hauling and activities within the pit, and confirmed that the (MiniMPL) lidar technology is suitable for detecting PM_{10} plumes from specific dust-generating events.

The field monitoring also involved a calibration of the lidar with conventional real-time particulate (DustTrak) monitors, completed at Mount Thorley Warkworth (MTW) mine. This revealed that there is a relationship between the cross-polarised components of the normalised relative backscatter (NRB_{cross}) recorded by the lidar and PM_{10} concentration. This relationship was used to infer indicative PM concentrations during field monitoring.

Field monitoring at MTW established that the lidar was able to identify PM_{10} plumes crossing the fence line, and would therefore be useful in providing early warning of the potential for boundary exceedances caused by site activities.

The outcomes of the monitoring confirm that the technology is suitable for use on an open-cut coal mine to identify sources of dust emissions, indicative concentrations and particulate matter (PM) movement under different meteorological conditions across critical site boundaries including fence lines and open pits.

Keywords: Lidar, Mining, ACARP, operational dust control

1. Introduction

1.1. Study Overview and Objective

Pacific Environment was awarded a grant (ACARP project number: C25029) from the Australian Coal Association Research Program (ACARP) to investigate suitable options and implement a field trial of a real-time monitoring method to provide accurate detection of particulate matter (PM) movement across significant, and critical, sections of a site boundary.

The objective was to assist the mining industry (in particular open-cut mining) by providing early detection of adverse PM movements across site boundaries with this real-time information, enabling better management of the on-site dust emissions, reducing unnecessary dust stoppages and improving general air quality in the area.

The study involved three stages:

- The completion of a desk-top literature review and comparison of the open-path monitoring technologies currently available both in Australia and internationally. This step aided in the identification of the most suitable technology to use during the study.
- Consultation with industry partners / site personnel to identify specific mine sites and locations for carrying out testing. Detailed site visits were then undertaken to the selected mine sites/monitoring locations, work programs were compiled, and the project design was developed.
- Completion of the field study / data analysis. This involved a number of monitoring campaigns to ensure representative data was collected. Data was then analysed and the ACARP report document (Pacific Environment, 2017) was developed. This report detailed the outcomes of the field demonstration and suggested that field studies such as this may be replicated / augmented by the industry for ongoing dust management purposes.

1.2. Background

Open cut mining activities have the potential to generate airborne PM due to the extensive areas exposed to wind erosion, as well as the methods of; overburden removal; coal extraction; loading and transport employed at any particular mine.

The PM measured on any mine site is comprised of the natural background aerosol loading of the atmosphere with the addition of the locally generated components from the mining activity. Coarse PM generated from a mine readily falls out of the atmosphere due to gravity, within tens to hundreds of metres of the source, and will have little impact beyond the site boundary during low wind conditions. Finer PM with an aerodynamic diameter equal to or less than 10 µm (PM_{10}) can be transported over longer distances and are considered inhalable. These particles are of public concern due to their ability to enter the respiratory system. PM with an aerodynamic diameter equal to or less than 2.5 µm ($PM_{2.5}$) are also of concern due to their small size, allowing them to enter and remain within the bronchi and lungs. Short-term and long-term exposure to both PM_{10} and $PM_{2.5}$ are associated with adverse health outcomes (WHO Regional Office for Europe, 2013). In New South Wales (NSW), coal mines are estimated to be the largest source of anthropogenic PM_{10} and $PM_{2.5}$ emissions (NSW EPA, 2012a, 2012b).

In addition to health effects, PM emissions from coal mines can lead to the deterioration of local amenity due to deposited and airborne dust, reduced operational efficiency caused by reduction/cessation of mining activities under adverse wind conditions, higher operating costs at the mine as a result of dust control measures, and potential restriction of the expansion of mining activity, especially where local communities are affected.

Traditionally, PM is measured using single-point monitors of various types, usually at ground level. The performance of single point monitors in accurately determining particulate loading is very much determined by their placement with respect to the sources of PM and the prevailing wind direction. More recently, open-path monitoring systems have been promoted by regulatory agencies, such as the US EPA (2006), due to the ability to measure along a path length of hundreds of metres. This allows for an integrated measure of PM moving through a line, as opposed to reliance on single monitoring points.

The key open-path methods that can be utilised for monitoring PM at open-cut coal mines are open-path laser transmissiometers (OPLT) and Light Detection and Ranging (lidar) systems. Of these, lidar is the technology which is able to provide a three dimensional (3-D) view of the movement of suspended particulate matter. It has the capability to map PM movement across a boundary by monitoring a two dimensional plane extending vertically and horizontally in close to real time.

2. Principles of Lidar Technology

2.1. Lidar System Overview

Lidar systems are mostly commonly used for measuring atmospheric conditions, such as the height of the planetary boundary layer (PBL) and cloud thickness. For such applications, fixed ground-based lidar systems typically point directly upwards at an elevation of 90°. However, it is also possible to have lidar systems scanning at elevations less than 90°. This provides information on the distribution of aerosols in the atmosphere at a particular altitude.

A Mie backscatter lidar operates using a laser that emits a pulse which is detected both to start the timing clock, and to measure the energy contained in that pulse. The timing clock is usually an oscilloscope or digitiser of sufficient (35 MHz) bandwidth to record a signal typically every 30 nanoseconds (ns).

This is sufficiently fast that the range resolution of the lidar becomes 5 metres (m), calculated from the speed of light divided by the bandwidth and a factor of two to account for the out-and-back passage of the light.

Implicit in this is that the laser pulse is shorter in duration than 8 ns, i.e. its physical spatial length should be 2.5m in order to account for the uncertainty of whether a scattering event should happen at the leading edge or the trailing edge of the pulse. Thus the range resolution is set by the choice of the hardware used in construction (Figure 1).

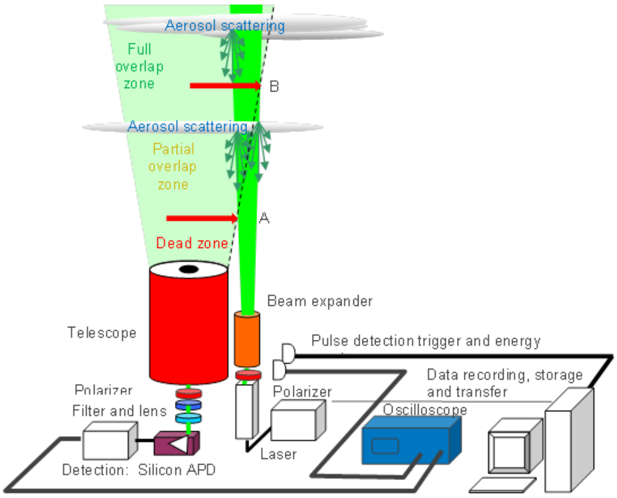

Figure 1. Schematic setup of a typical Mie scattering lidar system

Figure 1 also shows a dead zone (also commonly referred to as the 'blind zone') where the laser beam and the telescope field of view do not overlap and the acquisition of signal is meaningless. Between the red arrows labelled A and B, the overlap ranges from zero to 100%. Above arrow B there is full overlap. The presence of a blind zone means that data captured in the area where the laser beam and the telescope field of view do not overlap cannot be reliably used.

2.2. The Lidar Equation

The formula appropriate to particulate material detection by lidar in the lower atmosphere is well documented, and is referred to as 'the Lidar equation'. This formula is shown in equation (1) below.

$$P_\lambda(R) = P_{\lambda 0} A_0 \kappa(\lambda) \xi(R) c \tfrac{\tau}{2} \beta(R,\lambda,a) \frac{1}{R^2} \exp(-2\int_0^R \alpha(r,\lambda)dr) \quad (1)$$

This formula gives the received power at the detector based on the variables which are:

- The power of the outgoing laser of wavelength λ; $P_{\lambda 0}$ (W)
- The area of the telescope used for detecting the return signal; A_0 (m^2)
- The efficiency of the optical system at the wavelength λ; K(λ)
- The overlap function between the source expander and the telescope (this will vary between zero and 1); ξ(R)
- Range R at which the backscattered signal is sourced, as determined by the speed of light times half the time taken. This factor accounts for the geometric decrease in signal as the laser pulse goes further away from the telescope; $1/R^2$ (m^{-2})
- The speed of light; c (m/s)
- The duration of the pulse of laser light used; τ/2 (s)
- Back scattering coefficient which is the reflected laser radiation due to Mie scattering from the particulate material and the atmospheric molecules; β (R, λ, a)
- The integrated extinction coefficient which is the absorbance of the atmosphere at that wavelength for the passage up to the scattering site at range R and back, as shown in equation (2):

$$\exp(-2\int_0^R \alpha(r,\lambda)dr) \quad (2)$$

All lidar units have inherent limitations and assumptions associated with their operation. The latter two parameters detailed above (the backscatter coefficient and the extinction coefficient) represent the two embedded unknowns within the Lidar equation. Solutions to the Lidar equation therefore involve assumptions about the atmosphere in which the lidar is used, as well as the relationship between the backscatter and extinction coefficients. For this reason it is challenging for a lidar unit to easily determine the mass concentration of a particular sized particle in the atmosphere. A lidar system can, however, easily visualise the plume dispersal from a source in real time.

The relative signal strength will be related to the number of particles within a given volume of air, which in turn can provide indicative information on PM concentration.

3. Monitoring Equipment

3.1. Sigma Space MiniMPL system

As a result of the literature review performed in Stage 1 of the study, Sigma Space's MiniMPL lidar system was selected as the open path technology for the project. The MiniMPL is an elastic backscatter lidar and software developed by the Sigma Space Corporation. The MiniMPL system and laptop are housed inside a specialised environmental enclosure designed by Sigma Space with an optical transceiver unit which sits on the top of the enclosure. The optical transceiver houses the laser transmitter (operating at a visible green 532 nm wavelength), and the photon counting return signal detection system. The range resolved signal is collected and displayed in real time on the data acquisition computer.

A key feature of the Sigma Space MiniMPL is its capability to measure both the perpendicular and parallel polarisation components of the backscattered light. Since dust particles are typically non-spherical and polarise scattered light, the cross-polarised component of the normalised relative backscatter (NRB_{cross}) signal can thus be related to PM concentration in the atmosphere. This signal may provide a more accurate indication of the atmospheric PM mass loading than the co-polar (parallel) NRB measurement (NRB_{co}), which comes from spherical atmospheric aerosols (usually moisture) including water vapour, fog, mist and rain.

4. Study Areas

4.1. Sampling sites and constraints

There are a number of siting constraints that require examination when considering lidar implementation. The principal consideration is the availability of nearby power supply. Whilst a generator can be used to power a lidar unit, this would only be practical to consider for short term use due to the frequent refuelling requirement of the generator unit. For this reason, access to mains power was a major consideration when selecting the lidar monitoring locations.

Another potential limitation of the lidar equipment is that most lidar units have a 'blind zone' (refer Section 2.1). The MiniMPL has a relatively small blind zone, comprising the first ~100m of path length. The equipment was therefore placed approximately 100m back from the area of interest.

4.2. Mount Thorley Warkworth (MTW)

MTW is an integrated operation comprising two adjacent open-cut mines located 15km south-west of Singleton in the Hunter Valley region of NSW.

A site was selected along the fence line of MTW's eastern boundary that borders a major public road, the Golden Highway. This site was firstly chosen to provide a long, straight, flat and unobstructed path on which the lidar could scan and PM monitors could be placed along. Data was collected at MTW from 2 August to 9 August 2016

The lidar path length at MTW was 600 m, with DustTraks placed at 200 m intervals along this path (Figure 2). The lidar was set to scan at a constant azimuth with varying elevations of 2.0, 2.5, 3.0, 3.5, and 90° at 15 second intervals with a 5m resolution. Power to the lidar unit was supplied by a 15 kVA trailer-mounted diesel generator, which was positioned a few metres to the north of the lidar. It is considered unlikely that diesel emissions were detected by the lidar since, as noted above, the MPL has a minimum blind zone of 100 m from the unit itself. Data was collected at MTW from 2 August to 9 August 2016.

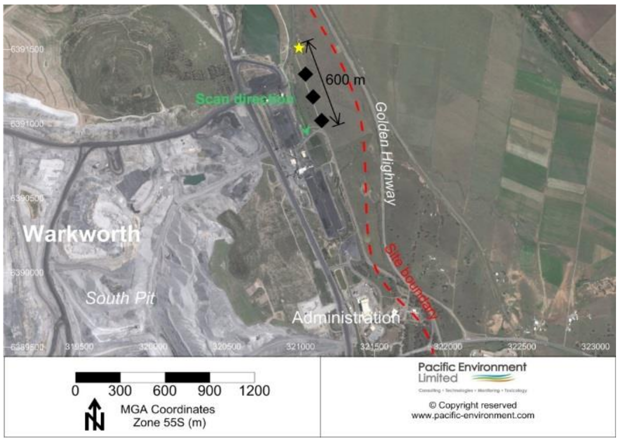

Figure 2. Lidar system at MTW (yellow star) and PM monitors (black diamonds). Lidar scan direction shown in green and site boundary shown as a dashed red line

4.3. Hunter Valley Operations (HVO)

HVO is a large mining complex located approximately 18 km west of Singleton in the Hunter Valley region of NSW. This site is a multi-pit open cut mine that uses the dragline truck and shovel method for coal extraction. It is operational 24 hours a day, seven days a week.

The selected site for the lidar trial was located at the north-western side of HVO's Cheshunt Pit (Figure 3). The MiniMPL unit was set to scan along the top of the high-wall to the south-east, which resulted in an azimuthal range of approximately 25°. The limits of the scanning range were controlled by a haul road located perpendicular to the high-wall. Two DustTrak units were positioned along the high-wall to measure PM_{10} at the far side of the pit from the lidar. In addition, one PM monitor was situated next to the lidar unit.

Lidar data was captured continuously from 6 July 2016 to 28 July 2016.

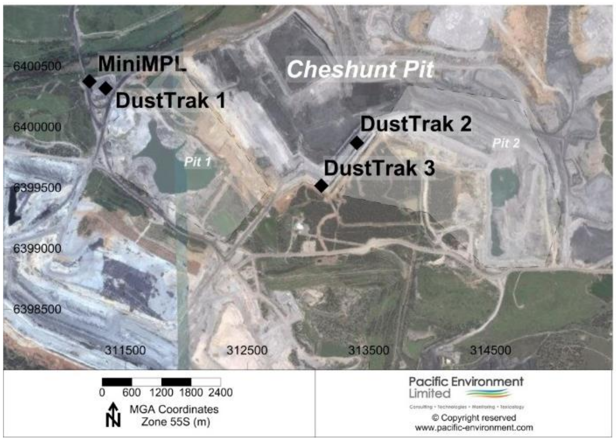

Figure 3. Lidar and PM monitor locations at Cheshunt Pit, HVO

4.4. Forth Scratchley, Newcastle

The Port of Newcastle is the largest bulk shipping port on the east coast of Australia and the world's leading coal export port (Port of Newcastle, 2016). The lidar unit was set up at Fort Scratchley, which is a historical fort located on the hill of a narrow peninsula between the Pacific Ocean and the Hunter River (Figure 4).

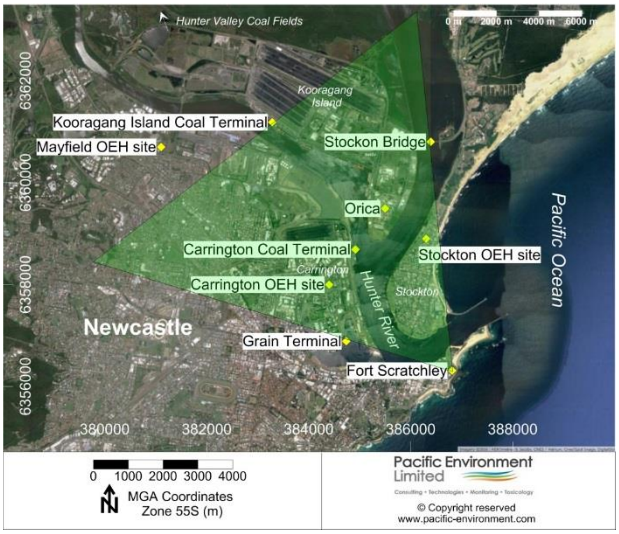

Figure 4. Port of Newcastle and surrounding area with lidar scan area shown in green

The site is ideal for a regional-scale scan of the port activities due to its elevated position 40 m above sea-level and clear views across the Hunter River The lidar scans ranged from a grain terminal to the west, to Stockton Bridge to the east, covering a range of approximately 70°. This range captured ship activity entering and exiting the Port of Newcastle as well as industrial activities including coal loading in the port region..

5. Data Analysis

5.1. Pre-processing

Unprocessed (raw) lidar data is simply a display of detector counts as a function of distance from the lidar unit. Distance is calculated from the measured period of time between the laser pulse leaving the unit and the time a signal returns. Given the fixed speed of light, this period accounts for the travel distance to the target and back, as well as the uncertainty in the range from the timing interval and the laser used.

Since the signal returning to the telescope decreases with distance from the lidar, this may be corrected for by multiplying the received signal with the range distance squared. This is referred to as the range corrected signal (R^2 Corrected).

The lidar data collected was corrected for the dead time, after-pulse, and overlap using calibration files supplied by Sigma Space specific to the unit being used. Further explanation of these correction factors is provided within Pacific Environment, 2017.

As noted in Section 2.2, the backscatter and extinction coefficients are specific to the atmosphere in which the lidar is used, and represent two embedded unknowns within the Lidar equation. Solutions to the Lidar equation require assumptions as the value of these coefficients, as well as the relationship between them. This is addressed through reference to the 'lidar ratio'; the ratio between the optical extinction and the backscatter. As the SigmaMPL equipment is not able to measure lidar ratio, this was estimated based on ratios reported in the literature. As higher lidar ratios are expected to result from coal mine related PM due to the presence of large, absorbing particles, only lidar ratios (λ = 532 nm) previously reported for polluted continental regions were considered for this study. These regions included the Asian outflow region in the western Pacific, the Pearl River Delta in China, and northern and north-eastern India. Studies reported lidar ratios in these areas to be 46 ± 9, 46, and 49 ± 19 respectively (Anderson et al., 2003; Ansmann et al., 2005). Based on an average of these values, a lidar ratio of 47 has been estimated for the Hunter Valley coal mines.

5.2. Post-processing

Post-processing the data included calibrating lidar backscatter data with PM_{10} measurements recorded by the DustTrak units along the fenceline at MTW (see Section 4.2). Calibration involved the use of lidar data collected from 0 – 600 m of the lidar unit along the test path at MTW. These data had a temporal resolution of 15 s. The lidar data was then binned into 200 m intervals: 0 - 200 m, 201 - 400 m and 401 - 600 m to match the 200 m placement intervals of the DustTraks (see Figure 2). To compare the relationship between backscattered lidar signals and PM_{10} concentrations, all data was smoothed by averaging to a 1h resolution.

6. Results and Discussion

6.1. Correlation between measured parameters

Concurrent observations of the measured backscattered lidar signals (Aerosol Optical Depth (AOD), normalised relative backscatter (NRB)), PM_{10} concentration (measured by DustTraks), and meteorological data from the calibration exercise at MTW were examined.

Peaks in PM_{10} concentrations were found to correlate best with the NRB_{cross} signal. A paired two sample t-test for mean averages yielded a coefficient of 0.744. Fitting a power law equation to PM_{10} concentrations vs NRB_{cross} showed a correlation of R^2 = 0.642 (Figure 5).

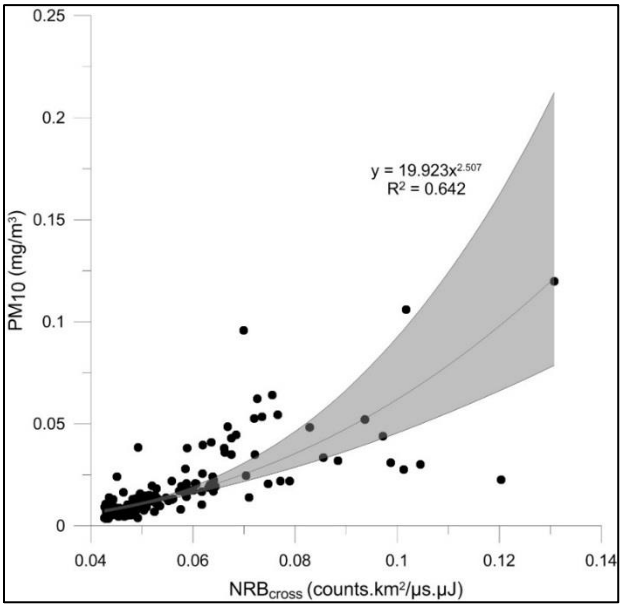

Figure 5. PM_{10} vs NRB_{cross} where grey shaded area represents the 90% confidence interval

The power law equation for relating NRB_{cross} to PM_{10} concentrations is given as:

$$PM_{10} = 19.923.NRB_{cross}^{\ 2.507} \quad (3)$$

where PM_{10} is in mg/m³ and NRB_{cross} is in counts.km² / µs.µJ.

There was less correlation between PM_{10} concentrations and the NRB_{co} signal. Several peaks in NRB_{co} signal were observed during the MTW calibration exercise and were identified as being related to increases in the relative humidity (and thus spherical water aerosol).

Interestingly, the data showed no correlation between the AOD and PM_{10} concentrations. Previous studies have shown a strong positive correlation between these two parameters. The reason for this may be due to previous studies having derived the AOD from satellite-based lidar measurements whereas the MiniMPL lidar retrieves AOD data from ground-based measurements collected by AERONET (http://aeronet.gsfc.nasa.gov/new_web/index.html), of which the closest monitoring site is in Canberra, NSW. Without site-specific AOD values, this parameter is not considered to be useful in this study for estimating PM_{10} concentrations.

Similarly, there was no correlation between the extinction coefficient and PM_{10} concentrations, with peaks in the extinction coefficient observed to be out of phase with PM_{10} concentrations.

This may reflect the limitation of assuming a constant lidar ratio (discussed in Section 5.1), which is then referenced to calculate the extinction coefficient. Furthermore, the MiniMPL system calculates the extinction coefficient referencing the parallel component of the backscattered light. As there was a relatively low correlation between the NRB_{co} signal and PM_{10} concentrations, limited utility was derived from referencing a calculated extinction coefficient in estimating PM_{10} concentrations.

As a result of these findings, NRB_{cross} data was considered the most reliable parameter for the estimation of PM_{10} concentration and was therefore used to infer PM concentrations.

6.2. Inferred PM concentrations referencing lidar observations

6.2.1. Fence-line monitoring

Background / observed PM_{10} concentrations at MTW fenceline were low and remained low throughout the dust events (and throughout the calibration / fenceline observation exercise as a whole). The inferred (short-term peak) PM_{10} concentrations from the NRB_{cross} signal were up to 100µg/m³. The length of the primary dust plumes were observed to be up to 100 m and extended from an elevation of around 10 m – 40 m. Plume migration events were observed by the Lidar for short periods of less than five minutes. These low plume frequencies and concentrations are to be expected considering that the MTW site was not in close proximity to any major sources of PM emissions such as blasting, with the coal conveying and stockpiling in the immediate area well controlled in terms of dust management.

6.2.2. Blast event monitoring

There were nine scheduled blast events during the monitoring period that occurred in the vicinity of the MiniMPL at HVO during the monitoring period. One such example was a blast event captured on 15 July 2016. On this day, elevated NRB_{cross} signals were detected following the blast event at 13:14. The results from the NRB_{cross}/PM_{10} calibration at MTW were used to infer PM_{10} concentrations. Initially following the blast at 13:15:09, the PM_{10} emitted from the blast was concentrated in a rectangular area approximately 500 m x 500 m, and an elongated area approximately 1000 m x 50 m. In these areas, PM_{10} concentrations were inferred to be > 5 mg/m³. The background PM_{10} concentrations were > 50 µg/m³.

Five minutes after the blast, the area in which PM_{10} concentrations were > 5 mg/m³ had approximately doubled to cover an area of 1,000 m x 1,000 m. In addition, the plume had dispersed significantly.

An example of the blast event at 13:14 overlain onto satellite imagery is shown in Figure 6. It is anticipated that this type of visualisation could be provided in real time to monitor dust plumes from blasts and other dust-generating events with some limited adaptation to existing data visualisation software.

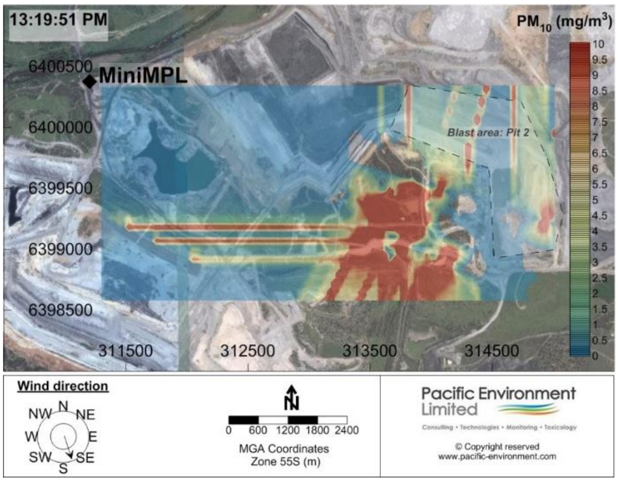

Figure 6. PM_{10} concentrations over Cheshunt Pit, HVO during a blast event on 15/7/16 mapped onto satellite imagery of coal mine

6.2.3. Regional-scale lidar monitoring

The outcomes of regional-scale lidar monitoring is represented by the results from scanning over the Port of Newcastle, with the MiniMPL located at Fort Scratchley. The NRB_{cross} data from lidar scans at 33.5° were compared with PM_{10} and $PM_{2.5}$ TEOM monitoring data at the OEH Stockton ambient air quality monitoring station, located approximately 3 km from the MiniMPL lidar, to evaluate whether a correlation was evident.

It was identified that no mathematical correlation was evident between NRB_{cross} and PM_{10}, or NRB_{cross} and $PM_{2.5}$. This is likely to be a function of the separation distance between the two monitoring techniques (~3km) along with the relative data paucity provided by the lidar in this scanning mode.

Regarding this latter point, it is highlighted that due to the lidar set-up described in Section 4.4, the lidar only made a single observation above the OEH Stockton TEOM site once every 40 minutes, with this instantaneous measurement then being compared against an hourly averaged observation from the TEOMs.

Further, the relatively low concentrations of PM observed at the OEH Stockton site indicate that there would have been a high signal to noise ratio within equivalent lidar measurements.

6.2.4. Monitoring of shipping movements

A summary of major shipping movements was collated during the monitoring period at Fort Scratchley. The lidar data during these time periods was then evaluated to assess the effects of shipping movements in the harbour. Plots of NRB_{cross} and NRB_{co} signals when large bulk coal carriers passed in front of the MiniMPL beam were produced. Of interest, these events were not detected in the NRB_{cross} plots. However, some of these events were detected by NRB_{co}. This suggests that the detected aerosols were potentially water vapour from the condensing of engine exhaust gases.

The lidar observations at Fort Scratchley represent a rich data source that has not been fully examined within this work. It is intended that these data be further mined within future scientific papers.

7. Conclusion

Mine site field measurements identified particulate emissions from blasting, hauling and activities within the pit, and confirmed that the MiniMPL is suitable for detecting PM_{10} plumes from specific dust-generating events. This study found no correlation between PM_{10} concentrations and the AOD, or PM_{10} concentrations and the extinction coefficient during monitoring. The calibration of the lidar with conventional DustTrak monitors, however, revealed that there is a relationship between the cross-polarised components of the normalised relative backscatter (NRB_{cross}) with PM_{10} at Mount Thorley Warkworth mine. There was somewhat less correlation between PM_{10} concentrations and the NRB_{co} signal, particularly at MTW and HVO. Monitoring at a range of sites demonstrated that both spherical and non-spherical aerosol plumes can be identified using the NRB_{co} and NRB_{cross} lidar data respectively.

The outcomes of the monitoring confirm that the technology is suitable for use on an open-cut coal mine to identify sources of dust emissions, indicative concentrations and particulate matter (PM) movement under different meteorological conditions across critical site boundaries including fence lines and open pits.

It is considered that the technology transfer from atmospheric aerosols measurement using lidar to measurement of industrial dust sources is not trivial. While the technology has great potential, it is essential that it be deployed and interpreted properly.

Potential areas for future work include investigation of:

- Longer term field trials of lidar instrumentation at additional mine fence lines or open pit locations, co-located with conventional particulate monitoring.
- Investigation of the relationship between PM_{10}, extinction and NRB_{cross} at particulate concentrations < 50 µg / m^3.
- Calculation of a region-specific extinction coefficient and the aerosol optical depth (AOD) in the Hunter Valley which would improve the accuracy of the PM concentration calculations.

- Use of direct extinction measurement through the dust plume concurrent with Lidar observations.

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