Information Paper on sensor and monitoring technologies

Submitted to the Office of the NSW Chief Scientist and Engineer by Professor Ben Eggleton, School of Physics, University of Sydney

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Executive Summary

We review currently available instrumentation for the measurement of dust particulates suspended in air. We divide the instrumentation into three categories: instruments which are calibrated to provide absolute measurements, lower-cost instruments that use similar measurement principles but which are not calibrated, and a new category of easily-networked, low cost, smartphone-compatible monitoring tools that are being deployed in citizen science networks. Instruments in the first two categories measure particulate matter and other components of air quality at a single point and are used to infer ambient air quality. In many cases, integration times needed to obtain a reliable measurement are hours or more.

There appears to be evidence from published and other studies that there are high levels of pollution associated with the passage of coal trains. In terms of ambient measurements, the NSW Office of Environment and Heritage is using techniques and instrumentation at or near current best international practice. These techniques may not be appropriate for measuring small-area dust plumes on an ongoing basis because the localized, transient nature of such plumes is not easily detected or quantified by a highly dispersed network of sensors designed to measure ambient air quality over a very large area.

We discuss 'open path' approaches to monitoring and measurement of pollution in which measurements are integrated along the path of an optical probe. These have real time temporal resolution and can make integrated measurements over kilometres. These characteristics appear to be better suited to the detection and quantitative measurement of coal dust plumes.

The identified shortcomings of ambient measurements of air quality along the corridor suggest that the OCSE consider a study into the feasibility of deployment of an open path monitoring system. It is believed that a system of this type would provide benefits to counter the spatial and temporal resolution issues associated with current point detection systems. Approaches to unfold the distribution of particle sizes along the path would need to be investigated, along with proof of principle demonstrations of the necessary signal sensitivity. The use of a commercially- available open path Fourier transform infrared (FTIR) instrument could also be considered as part of the same study for monitoring gaseous pollutants associated with coal trains. Such instruments are used extensively overseas for similar purposes.

Glossary of definitions and acronyms used in this report

HVAS	High volume air samplers
OEH	NSW Office of Environment and Heritage
PM_1, $PM_{2.5}$, PM_{10}	The mass density or concentration(measured in μg/m^3) of particles in air whose size is less than 1, 2.5, or 10 μm
Report	The initial report of the review of coal dust emissions management practices in the NSW Coal Chain conducted by the NSW Office of the Chief Scientist and Engineer.
TEOM	Tapered element oscillating microbalances
ToR	The Terms of Reference for this report, listed in Appendix 1.
TSP	Total Suspended Particulates

Introduction

This Report was commissioned as part of a review of coal dust emissions management practices in the NSW Coal Chain conducted by the NSW Chief Scientist and Engineer. The initial report of the review (the 'Report') determined that "there has been a substantial set of activities undertaken over a number of years in the Hunter rail corridor both to measure and to reduce dust and particulates. However there are no existing studies or sets of studies available to date that can definitely determine if there is a problem. The available studies provide partial information about specific issues."

The study goes on to say that "The gaps in our knowledge exist around localized emissions in and near the rail corridor. Studies indicate that there are increased levels of dust in the rail corridor when some trains pass; **but less well understood is the composition of the dust, its source, quantity, concentration and pattern and distance of dispersal**."

The aims of this Report are to

1. provide information and expert advice about current techniques and instrumentation including capabilities and limitations
2. advise on future techniques and instrumentation that may address concerns raised in the Report,
3. comment on additional benefits that could be provided through the use of novel sensor designs.

The Report addresses the Terms of Reference set in the Review's Initial Report (Appendix 1). Broadly speaking, the Report provides an overview of current and emerging monitoring, measurement and sensor technologies that could be used for sampling and monitoring coal dust and related emissions from the coal chain in the rail corridor.

Context

Many major cities around the world have air monitoring networks with publicly accessible information on the concentrations of the major pollutants produced by motor traffic and industrial activity (see for example, the London Air Network http://www.londonair.org.uk).

In NSW, ongoing concern has been expressed by community members and groups in the

Hunter region about the environmental and human health impacts of dust and particle emissions associated with coal trains that connect the region's mines to the Port of Newcastle. Dust and emissions could originate from the coal itself, from emissions from the diesel locomotive, and from dust stirred up from the ground as the train goes by. These points are covered extensively in the Report.

Monitoring of particulate matter by sampling

In this section we discuss the currently-used techniques and instrumentation for monitoring ambient particulate and suspended matter (aerosols).

Deposited dust sampling - this is usually done on a monthly basis using the Australian Standard 3580.10.1 method for measuring deposited particulate matter (units of g/m^2). This method involves the sampling of particulates deposited into a glass bottle through a stoppered funnel; the top of the funnel is positioned 2 m above the ground surface to avoid the possibility of grains saltating (bouncing) into the funnel. This is not a very aerodynamically efficient collection method (see Sow et al 2006) - inverted frisbees have also been tried as an alternative, but all such open-topped devices suffer from fouling by birds unless spikes are employed, but then these affect air-flow and dust fall. This method is supposed to estimate grains falling to earth, not those suspended in the air and travelling downwind. Particles less than 5 μm can stay suspended almost indefinitely until rained out, and it is rare for these traps to collect particles bigger than 200 μm.

Suspended particulate sampling

(i) High volume air samplers (HVAS) - Unlike deposited dust gauges, HVAS sample dust particulates that are suspended in the air, and so the total suspended particulates (TSP) measured by HVAS have the units of $\mu g/m^3$ (mass of particulates per volume of air). The particulates measured by HVAS usually have a particle size of 50 μm or less, as larger particles are generally too heavy to remain suspended in the air in moderate or light winds. HVAS can also be adapted (by cyclonic filtration) to collect only those particles finer than 10 μm (PM_{10}) or those particles finer than 2.5 μm ($PM_{2.5}$).

(ii) Tapered element oscillating microbalances (TEOM)

Like HVAS, TEOMs measure suspended dust particulates and report masses of dust in units of $\mu g/m^3$ (mass of particulates per volume of air). TEOM devices can measure total TSP, PM_{10} and $PM_{2.5}$ either separately or combined, and operate on a continuous basis. Measurements are usually reported as a daily average of 5 minute sampling intervals.

1. Calibrated Instruments

There are many instruments available commercially for the calibrated measurement of particulate matter. The majority of the detectors for particulate or suspended matter rely on the in situ collection of particles which are then weighed (eg TEOM) or measured optically as discussed in Table 1. Each of these instruments claims to provide calibrated measurements of TSP or PM. Comments on the accuracy of measurement expected from these instruments follow Table 1. A number of instruments are typically integrated into a single ambient monitoring station.

In addition to $PM_{2.5}$ and PM_{10} there is increasing attention being paid to the monitoring and measurement of ultrafine particles less than 0.5 μm. We have not addressed instruments for this purpose.

Table 1: Commercially-available air emission measurement technologies and instrumentation

Measurement method	**Description**	**Characteristics**
Deposition gauge	Dust deposits through a funnel onto filter paper which is then removed and weighed in a laboratory	No temporal resolution. Ideal for long term, low cost monitoring. Can be absolutely calibrated against traceable mass standards
HVAS	Sampler draws air through a cyclonic filter to select PM_{10}, $PM_{2.5}$, or PM_1 dust. Deposited dust can be weighed or measured optically remotely or in situ	Sampling periods generally hours or more. Different cyclone filters needed for each particulate size.
TEOM	Low volume air sampler with cyclonic filters to measure different particle sizes continuously by weighing	Needs 240V, special air -conditioned cabinet, concrete pad. Provides calibrated mass measurements. Accuracy: see note below
Beta gauge	Particles are deposited on a filter tape after size filtering. A Carbon-14 source produces β particles whose absorption in the tape (after calibration) is proportional to the mass of particles on the tape	Relatively small, lightweight. Sampling time depends on deposition rate of particles but is typically hours. Accuracy: see note below

Measurement method	Description	Characteristics
Grimm particulate monitor (Grimm Aerosol GmBH)	Sampled air is drawn into a chamber and irradiated by a focused laser beam. Light scattered by particulates is collected and analysed to estimate dust concentrations in the different particulate size ranges	Device is difficult to calibrate absolutely. Measurement range 0.1 $\mu g/m^3$– 6 mg/m^3
Particle detector	Air is drawn through an analysis chamber past a tightly focused laser beam. Particles are counted each time the laser beam is obscured	Used in clean rooms; can saturate at high pollution levels
Osiris particulate monitor (Turnkey Instruments P/L)	Pump draws air through a proprietary forward-scattering nephelometer (a device to measure light scattering in turbid media) to simultaneously infer concentrations of particle sizes from laser scattering.	Measures PM_1, $PM_{2.5}$, PM_{10}. Concentrations up to several mg/m^3 can be measured at resolutions of 0.1 $\mu g/m^3$. According to manufacturer the measurement to measurement uncertainty is quoted at 5 $\mu g/m^3$ but it is unclear if this refers to TSP or to the PM components. Accuracy also depends on the constancy of the volumetric flow in the sample chamber, quoted at better than 3%.
DustTrack particulate monitor (TSI Inc)	Simultaneously measures using optical scatter size-segregated mass fraction concentrations corresponding to PM_1, $PM_{2.5}$, Respirable, PM_{10} and Total PM size fractions	Battery operated, handheld, can be calibrated. Cost is \$5-10k depending on options Range is 1 mg to 150 mg/m^3.

Accuracy: The measurement uncertainty of TSP or PM components associated with each of these instruments depends on the method of calibration, measurement uncertainty (type A – statistical uncertainty and type B – systematic uncertainty), and instrumental resolution. Strictly speaking calibration uncertainties are type B uncertainties but are reviewed separately here. The principal limitations to uncertainty of measurement are as follows:

Table 2: Measurement uncertainties

Contribution to uncertainty	**Classification**
Fidelity of transfer of particulate concentrations in ambient air to instrumental measurement chamber	Type B uncertainty which varies from instrument to instrument and with method of deployment in the field
Changes in operating parameters of instrument over time	Type B uncertainty. An example is the change in flow rates in the Osiris measurement chamber as particles deposit on the pump filter (quoted at 3%)
Reproducibility of measurement	Type A uncertainty, either due to random variations in operating parameters of instrument (eg 5% variation in mass flow for HVAS systems) or statistical variations in measurement
Calibration of instrument	Type B uncertainty. A number of instruments (deposition gauges, TEOMs, Beta gauges) can claim absolute calibration through traceability to nationally-maintained mass standards, while for others (optical particle counters using scatter or obscuration) the method of calibration may rely upon calibration against 'standard' dust (sometimes referred to as "Arizona Road Dust"). The National Institute of Standards and Technology (USA) provides RM8362, a naturally occurring, irregularly-shaped heterogeneous mineral dust for use as a secondary calibration material for particle sizing instruments over the range 1 – 20 μm.

There have been a number of recent studies in which the field performance of a number of particulate-measuring commercial instruments was inter-compared (for example, Halliburton et al 2007, Walden et al 2010, De Jonge et al 2008).

In a series of experiments in the Hunter Valley Halliburton et al compared the performance of four Osiris units and found systematic variations of ± 15% even though the linear response of each unit was better than 3%. The readings of $PM_{2.5}$ obtained by a Grimm instrument were around 50% higher than those made by an Osiris and a TEOM instrument. The authors found that 24-hour averaging times were needed to get good correlations; the scatter in the data rendered comparisons almost meaningless for averaging times of 60 minutes.

De Jonge et al. inter-compared 11 particle monitors (optical, TEOM, Beta attenuation) over 5 months. Their conclusion was that "The ultimate monitor, quick in response and equivalent to the reference method without correction, has not been found... it is very difficult for automated monitors to meet (current) quality demands of the EU on $PM_{2.5}$ for a Limit Value of 25 µg/m^3."

Other studies (Walden et al 2010, Hains et al 2007) suggest that variations in measurement of $PM_{2.5}$ are associated with the chemical composition of the particulates.

2. Non-calibrated instruments

There are a number of units sold for non-professional use, for example for dust monitoring in the home, or for personal use as a handheld or belt mounted instrument. The ubiquity and affordability of these instruments merit their inclusion in this review in the situation where a 'mesh' of many tens or even hundreds of point measurement instrumentation be contemplated. Issues relating to calibration, repeatability, and robustness for outdoor use would need to be evaluated. Non-calibrated particle measuring systems are summarized in Table 3.

Table 3: Non-calibrated particle measuring systems

Manufacturer	**Measurement principle**	**Comments**	**Typical pricing**
Dylos Inc (USA)	Laser particle counter (obscuration of a focused beam)	Quotes "2 size ranges - small (bacteria, mold, etc) large (pollen, etc.)"	$200 - $500
TSI Inc - SidePak Personal Aerosol Monitor	Laser photometer	Belt mounted, less than 400 g. Shows real-time aerosol mass concentration And eight-hour time- weighted average	Not known but marketed as a personal monitor
Various	Modified smoke detectors (ionisation)	See Litton et al (2004)	$10s of dollars
AethLabs – the microAeth®	The air sample is collected on T60 (Teflon coated glass fiber) filter media, and analyzed in real time using laser absorption	Real-time, pocket-sized Black Carbon aerosol monitor	Not known

3. Citizen science monitoring

Finally, a number of low cost sensors are coming on to the market for use in “Citizen Science” air monitoring networks. These devices are not calibrated in any way that would provide data to NEPM standards, but when used by many people spread across for example a city the accumulated data provides an unprecedented spatial density of information that can provide insights previously unavailable. Three such units, which have been deployed to some success in The Netherlands and the USA are listed below. It is not unreasonable to expect that such ‘citizen science’ sensor networks will soon be deployed in Australia. This approach seems reasonable for a relative measurement but perhaps not for an absolute measurement. Increased reliability would require a ‘calibration’ against something like a NEPM monitor.

iSpex ((http://ispex.nl/en/)

A small optical attachment to the Smartphone camera as shown in Fig 1 below measures flux, degree and direction of polarisation of light in the camera field of view across the spectrum to infer aerosol concentrations integrated along the field of sight. On board instruments (GPS, inclinometer etc.) of the smart phone yield the geographical location and direction of orientation. These are recorded simultaneously with the measurement. Measurements from all users are uploaded to a central data base and combined to yield dust particulate measurements across the Netherlands like that shown in Fig 2.

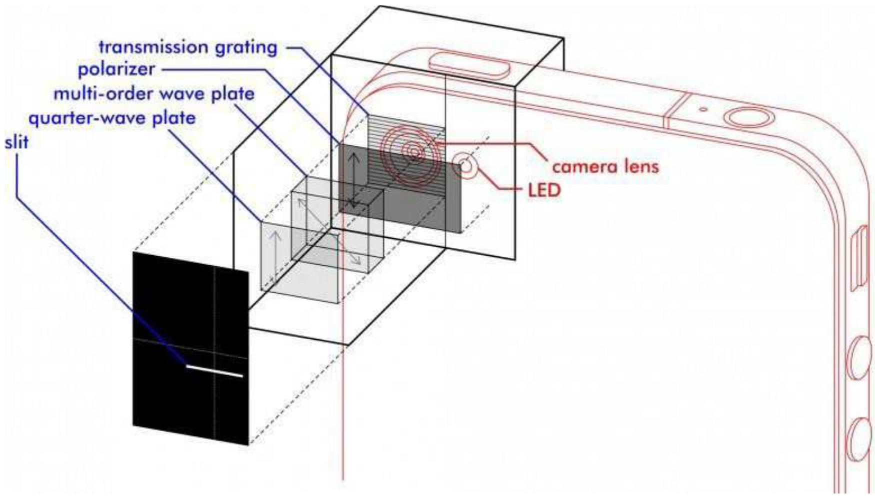

Fig 1: Reproduced from http://ispex.nl/en/techniek/ showing the iSpex attachment to a smart phone

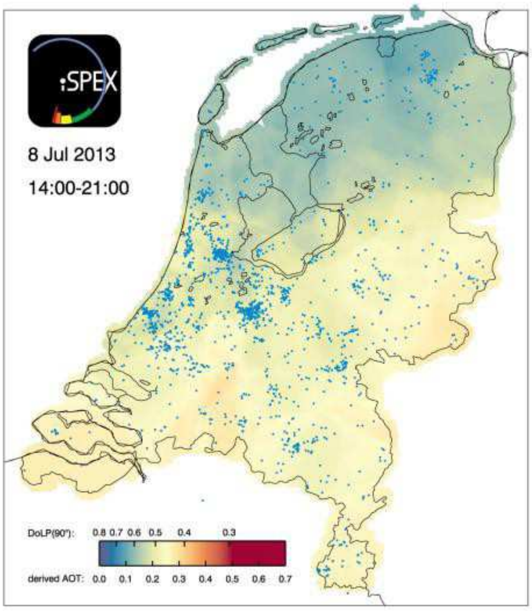

Fig 2: iSPEX map compiled from all iSPEX measurements performed in the Netherlands on July 8, 2013, between 14:00 and 21:00. Each blue dot represents one of the total of 6007 measurements that were submitted that day. At each location on the map, the 50 nearest iSPEX measurements were averaged and converted to Aerosol Optical Thickness, a measure for the total amount of atmospheric particles. Source: http://onlinelibrary.wiley.com/doi/10.1002/2014GL061462/abstract

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EPA (US Government) Citizen Scientist network (http://www.epa.gov/air-research/air-sensor- toolbox-citizen-scientists)

The US Environmental Protection Agency publishes a 'toolbox' for citizen scientists interested in monitoring the quality of air in and around their neighbourhood, place of work, etc. The toolbox gives operating instructions for a number of commercially-available instruments recommended by the EPA, guides on deployment of the sensor, guidance for data gathering and data analysis, and help with interpreting the results. Much of the information is published in a guidebook (Williams et al 2014), downloadable from the epa.gov website.

AirBox (Environment and Energy Engineering, the Netherlands)

The AirBox comprises an array of sensors, with particulate matter (incl. particle size distribution), temperature, relative humidity and GPS being standard. The AirBox also offers room for sensors that measure nitrogen and ozone. Multiple AirBoxes can be used to set up a network with a large spatial density. This network offers functions such as sending a signal when boundary values are exceeded and determining the location and emission of sources of pollution.

Networks of AirBoxes have been installed in Eindhoven and other Dutch cities. The synthesised pollution maps can be viewed online and used to plan cycling routes, low-pollution routes for children to work to school, etc.

See ftp://ftp.ecn.nl/pub/www/library/report/2013/f13039.pdf.

Present monitoring practices in NSW

The NSW Office of Environment and Heritage (OEH) maintains a network of sensors for monitoring particulate and noxious gases at locations across the state, with results available online (see http://www.environment.nsw.gov.au/aqms/index.htm). Table 4 provides details of what is measured, and the techniques used. Further information on the techniques used to measure concentrations of each pollutant can be found at http://www.environment.nsw.gov.au/AQMS/sampling.htm

Table 4: Air quality sensors used by OEH

Pollutant measured	Instrumentation/technique
Ozone	Ultraviolet spectroscopy (gas sampling in situ)
Oxides of nitrogen	Chemiluminescence (gas sampling in situ)
Ammonia	Chemiluminescence (gas sampling in situ)
Suspended matter	Integrating nephelometer: light scattering at 530 nm to measure particle sizes 0.1 – 2.0 μm
Particulate matter less than 2.5 μm ($PM_{2.5}$)	(1) Beta attenuation monitor (measurement time variable; depends on when glass tape saturated) (2) Differential mass measurement using a low volume air sampler (24 hour period)
Particulate matter less than 10 μm (PM_{10})	TEOM (can also be used for $PM_{2.5}$) (mass measurements accumulated over 30 minutes, 1 hour, and 8 hours)
Sulphur dioxide	Pulsed fluorescent spectrophotometry (gas sampling in situ)
Carbon monoxide	Infrared spectrometry (gas sampling in situ)

The OEH operates a network of 14 monitoring sites in the Upper Hunter and 6 in the Newcastle region to provide information on ambient concentrations of pollutants. The National Information Communication Technology Australia Centre of Excellence (NICTA) has applied machine learning algorithms to interpret the data from the array of point measurement systems and predict the evolution of the pollution over subsequent days (Guizilini et al 2015).

This network is not intended to detect highly localised plumes of coal dust nor is it likely to do so. The current monitoring system has a very low spatial sampling rate (14 stations in the Upper Hunter spread over a region of hundreds of square kilometers) and poor temporal resolution (hours to days) in so far as the detection of rapidly changing levels of pollution is concerned.

Monitoring coal plumes

The instrumentation in the current monitoring network samples pollutants in the air at the location of the instrument. In future studies of coal plumes the Report suggests that a much finer-grained network of sensors will be used: "There would be a number of monitors situated on both sides of the track, set at various distances from the track and at differing heights: in, around, and along a portion of the track. Information on the surrounding topography and land use of the area near the monitors would also be recorded. The monitors would be kept in place for enough time to draw out seasonal and meteorological impacts."

This comment begs the question of the correct sampling strategy for this situation. If implemented as suggested it would lead to significant costs in deployment unless low cost sensors such as those reviewed in Table 3 were used.

Some guidance on the monitoring strategy can be gained from studies of dust emission from coal trains both here and internationally. The Report lists (Appendix 4) nine in situ studies of pollution from particulate matter associated with passage of coal trains. The studies were conducted in both Australia and the US. Results ranged from 'no statistical difference' between trains and no trains passing while others quote increases as high as ten times ambient levels of PM_{10} for unloaded coal trains.

Recently, the results of a study of diesel and particulate emission from coal trains in the Columbia River rail corridor in Washington State were published (Jaffe et al, 2015). The authors monitored PM_1, $PM_{2.5}$, CO_2, and black carbon during the summer of 2014. They used a DustTrak DRX Aerosol Monitor placed alongside the rail track to obtain measurements of particle concentrations by size and used video cameras to identify the train type and speed. Of 74 coal trains that passed, 4 ("super dusters") had large plumes of coal dust emanating from some of the uncovered coal cars. These trains also had the highest peak $PM_{2.5}$ concentrations recorded during the study (53–232 $\mu g/m^3$), significantly higher than the maximum advisory concentration averaged over 24 hours of 25 $\mu g/m^3$.

The authors claimed that their results demonstrate that, on average, passage of a diesel powered open-top coal train result in nearly twice as much respirable $PM_{2.5}$ compared to passage of a diesel-powered freight train.

The news section of the Jaffe group website shows videos of several "super duster" train events, with plumes of dust clearly visible from a small number of the coal cars (see http://www.atmos.washington.edu/jaffegroup/modules/news/ under 'Train Research').

These studies suggest that emissions from coal trains are irregular in time but when they occur, the quantity of coal dust is substantial.

Comments on measurement techniques and networks

Despite the large number of techniques and instrumentation available, all suffer from one significant drawback as far as the measurement of coal dust from coal trains is concerned:

They do not have the necessary combination of three characteristics to definitively *determine the amount of coal dust released from a coal train as it passes:*

1. *Interrogation of a large enough area of observe localised events like dust plumes*
2. *High spatial resolution*
3. *High temporal resolution (less than one minute, the approximate time taken for a coal train to pass the observation station)*

An ideal monitoring system would provide a real time measurement of the concentration of particles immediately above the coal carriages as the train passes, and follow the dispersal of this dust plume once the train has past. Such monitoring characteristics might be more readily met with a long ‘open path’ system than a ‘point’ monitoring system.

‘Open path’ means that particulate and gaseous pollutants are monitored along a path rather than at a point. As an example, the total absorption of a laser beam along an optical path of several hundred metres is proportional to the concentration of airborne particulate matter integrated along the optical path that scatters the laser beam out of this optical path. A simple approach like this has excellent temporal resolution (for example, if the laser and detector were positioned on opposite sides of the railway track, several metres above the top of the coal wagon), but would have poor discrimination in terms of particle size distribution and the spatial distribution of the pollutants along the optical path.

The use of open path techniques for measuring gaseous pollutants is well established, especially for molecular species where absorption at spectral lines characteristic of the pollutant is the basis of the measurement technique. Differential Optical Absorption (DOAS) and Fourier Transform Infrared (FTIR) systems are well-established spectroscopic approaches with commercial instrumentation available since the early 1990s. These are discussed at the end of this section.

In principle, open path monitoring of particulates is possible using light scattering or light opacity – in fact, this is the basis of the measurement technique for instruments discussed in Table 1 (eg Grimm particulate monitor, Osiris, DustTrack). Light from a collimated optical probe, a laser for example, is scattered or fully obscured by particulate matter in the air path, allowing open path optical measurements of particulates by either optical absorption (opacity, measured as a reduction in the transmitted optical signal) or by optical scattering (measurement of light scattered at directions other than the probe direction).

Measurements of opacity can be related straightforwardly to the density or concentration of total suspended particulates integrated along the path of the optical beam. Assumptions about the distribution of particulates along the path – for example, a spatial dispersal pattern determined from the diffusion equation - can then be used to infer the concentration at each point along the path. Opacity monitors are commercially available from a number of manufacturers including Dynoptic, Teledyne, Land Instruments, and Forbes Marshall. The monitors are marketed for compliance monitoring in flues and ducts of industrial plants, where particulate levels are high so their suitability for monitoring particulate emissions from coal trains needs further consideration. However a very simple opacity monitor, the video camera used by Jaffe et al in their studies, successfully observed coal dust plumes. The application of opacity monitors to monitoring industrial processes is reviewed by Castellani et al (2011).

The scattering of light by particles is complex but it does allow particle size distributions to be determined. When the particle size is non-negligible compared to the wavelength of the optical probe the polarization and directionality of the scattering is described by Mie theory. The directional patterns of Mie scattering and Rayleigh scattering from spherical homogeneous particles (when the wavelength is much larger than the particles) are shown in Figure 3. The angular distribution of Mie scattering (and the total amount of scattered light) depends on the ratio of particle size to wavelength. These features make Mie scattering the basis of an attractive open path approach for the measurement of particle size distributions. The optimum wavelength depends on the range of particles to be measured and the optical dielectric properties of the particulates.

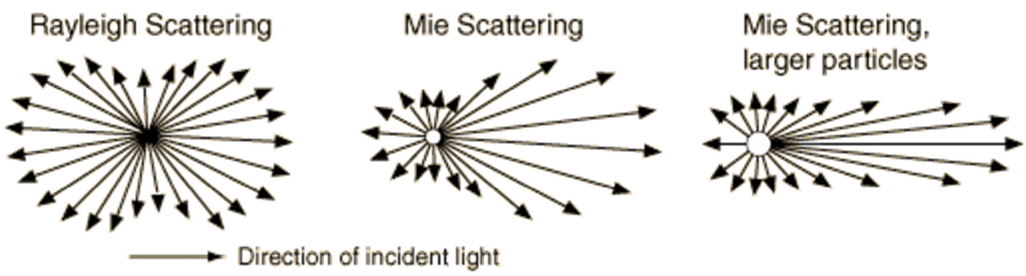

Figure 3: Directional patterns of Mie scattering and Rayleigh scattering (wavelength small compared to particle size)

Open path optical scattering has a substantial track record of deployment for environmental monitoring of dust and aerosols. Its use is well- established in remote sensing from space, where the long optical paths over which scattering occurs give good signals and high quality images (for examples of space-based imaging, see http://earthobservatory.nasa.gov/Images/). In the laboratory, the Malvern Mastersizer provides a proof of principle for this technique. It uses laser scattering to measure the size of particles by measuring the intensity of light scattered as a function of scatter angle and polarization as a laser beam passes through a dispersed particulate sample. This data is then analyzed to calculate the size of the particles that created the scattering pattern. Particle sizes measured range from 0.01 - 3500 µm with accuracy better than 1%. (http://www.malvern.com/en/products/product-range/mastersizer-range/)

Mention was also made earlier in this report of iSPEX, a smart phone compatible optical instrument that measures scattering from aerosols and particulates.

For monitoring of coal and dust particulate matter, concentration and particle size distribution are required. Careful calibration can lead to an estimate of total concentration, but calculations of the particle size distribution are not straightforward. The angular distribution of radiation scattered by particles of a given distribution of sizes can be calculated from Mie theory, but the inverse problem, calculation of the particle size distribution given an angular scattering spectrum, is not easily done. Rentz et al (2005) of Optra Inc (Boston, MA) propose an approach based on accurate calibrations of the measurement instrument for different particle sizes and application of least square algorithms. Unfortunately a search of their website does not reveal any subsequent commercial product based on this technology. This approach is similar however to that used to determine the mineral components in a rock sample from a broad spectrum measurement of reflectance by generating combinations of the reflectance spectra for 500 different minerals and optimizing the fit to the observed reflectance spectra using a least squares approach (Berman et al 1999).

It would be of interest to examine the feasibility of setting up a coal plume monitor based on scattering or diffraction of longer wavelength infrared light from $PM_{2.5}$ and PM_{10} dust plumes. The optimum wavelength range would be determined by a combination of factors: eye safety, availability of sources and detectors, and optimisation of performance in terms of discrimination of particles by size. In general, longer wavelength light is eye safe and would have much greater scattering cross sections and more easily measured diffraction patterns. A detailed analysis is outside the scope of this report but it should be noted that substantial expertise in the technology and equipment required for such a project exists in NSW Universities.

Monitoring of gaseous pollutants

Gas pollutants can be measured with open path FTIR or DOAS. DOAS uses a tunable or multiwavelength laser to measure absorption along the path in the centre of an absorption line of the species of interest compared to a second measurement well away from any absorption line. FTIR instruments use glow bar or other broad spectrum sources to measure absorption in the time domain as the path difference between the two arms of a Michelson interferometer is scanned; this is then fourier-transformed to calculate the absorption spectrum. Fig 4 shows a compact open path measurement system used for measuring concentrations of carbon dioxide.

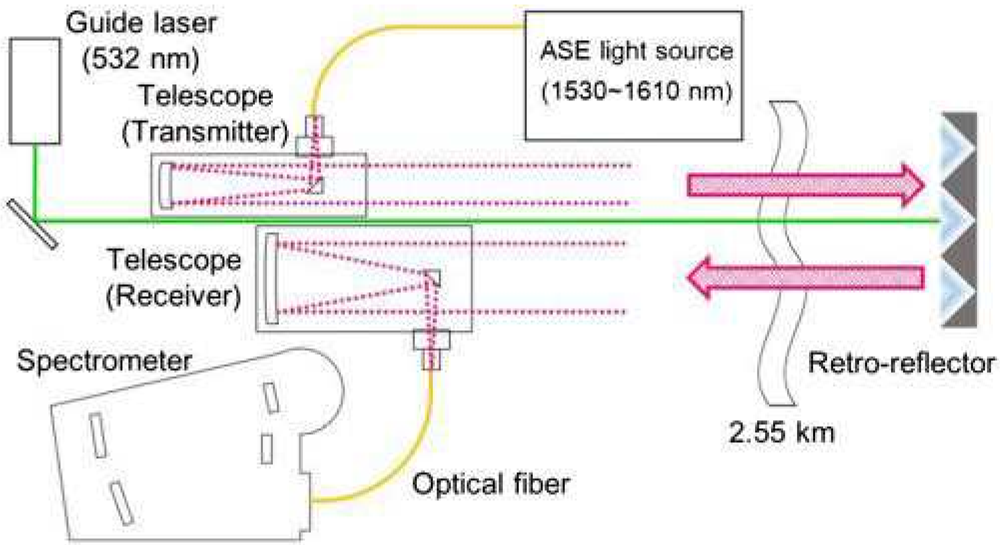

Figure 4: Example of an open path measurement system in which transmitter and receiver are in the one package and the measurement path is traversed twice (From Saito et al (2015))

These techniques are reviewed in the 2011 US EPA Handbook: "Optical Remote Sensing for Measurement and Monitoring of Emissions Flux" (available on-line at https://www3.epa.gov/ttnemc01/guidlnd/gd-052.pdf).

These techniques continue to evolve; for example Thoma et al (2008) from the R&D office of the US EPA report on the use of deep ultraviolet differential optical absorption spectroscopy (DUV-DOAS) to measure nitric oxide concentrations near a major highway. The advent of cheap tunable diode lasers has replaced expensive, power-hungry gas or solid state lasers in these techniques, making them more cost effective and able to be operated on battery power rather than mains power, hence more easily deployable.

Recent developments of broad band tunable laser sources in the near to mid infrared have allowed researchers to probe spectral regions in which common gaseous pollutants have very strong absorption lines (see Figure 5 below showing strong absorption of nitrous oxide lines in the mid IR). The strength of these absorption lines allows lower concentrations of pollutants to be measured with greater accuracy.

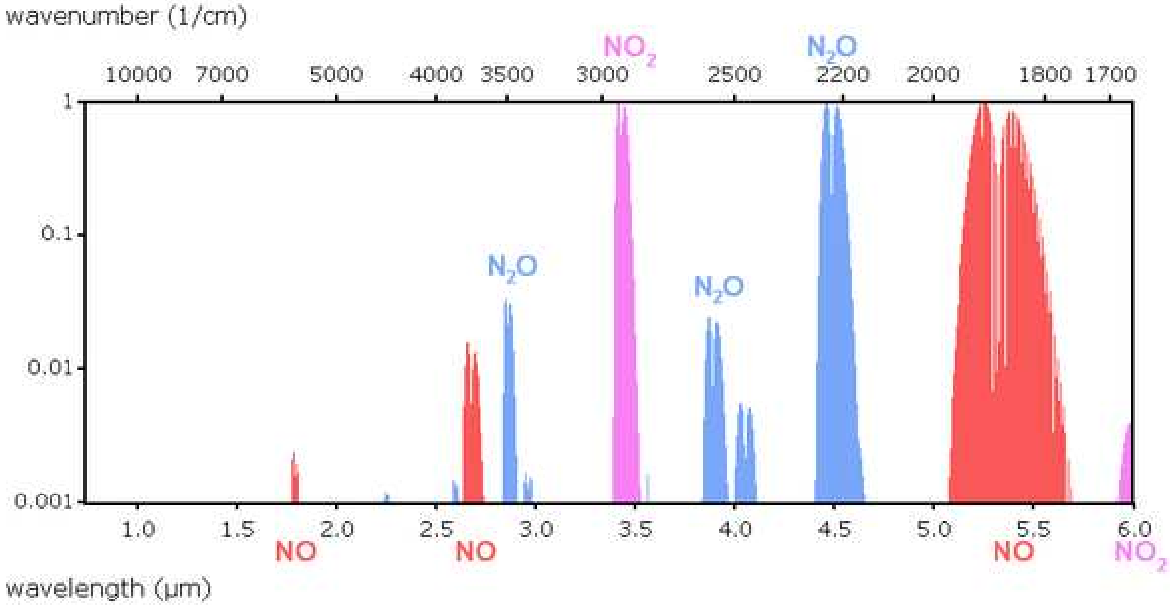

Figure 5: Absorption spectra of nitrous oxides (taken from http://nanoplus.com/en/applications/applications-by-gas/nitrogen-oxides-detection-nox/)

Conclusions

In terms of ambient measurements the OEH is using techniques and instrumentation at or near current best international practice. The only way of addressing the ongoing concerns of local community groups using the existing approach would be to dramatically increase the number of stations in the monitoring network, with a large increase in establishment costs and an even heavier burden of ongoing maintenance and data logging.

An open path monitoring approach would represent a significant change in direction for tracking air quality in the rail corridor. Implementation of a system would require the integration of off the shelf and commercially-available instrumentation with some customised components, special laser sources for example. Detailed consideration of a range of variables affecting the performance of such a system is necessary, so we recommend that the NSW Chief Scientist and Engineer consider a study into the feasibility of deployment.

Such a system might use scatter or absorption of an optical probe, almost certainly in the infrared, to monitor levels of dust associated with coal trains. Approaches to unfold the distribution of particle sizes along the path would need to be investigated, along with proof of principle demonstrations of the necessary signal sensitivity. The use of a commercially-available open path FTIR instrument could also be considered as part of the same study for monitoring gaseous pollutants associated with coal trains. Such instruments are used extensively overseas for similar purposes.

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Appendix 1: Terms of Reference for the Information Paper on sensor and monitoring technologies

To deliver an information paper to the “Review of rail coal dust emissions management practices in the NSW coal chain” being conducted by the Office of the NSW Chief Scientist and Engineer (OCSE) to provide information about advances in technologies for sampling, measuring and monitoring coal dust and related emissions particularly along the rail corridor.

1. The purpose of the Information Paper is to provide an overview of current and emerging monitoring, measurement and sensor technologies that could be used for sampling and monitoring coal dust and related emissions from the coal chain in the rail corridor.

2. This Information Paper will form part of the “Review of rail coal dust emissions management practices in the NSW coal chain”. This paper is likely to be publicly released and may appear on the website of the NSW Chief Scientist and Engineer.

3. The Information Paper should be developed having regard to the Terms of Reference for the Review (Schedule 5).

4. The Information Paper should include discussion of the following:

    a. Current monitoring, measurement, sensor and detection technologies for air pollutants associated with the coal train rail corridor including particulate matter, emissions and dust, etc.

    b. New and developing monitoring, measurement, sensor and detection technologies for air pollutants

    c. In relation to a) and b), include:

        i. a description of the technologies, including their limitations

        ii. the sensitivity and accuracy of the technologies in relation to particulate matter (PM) sizes (including PM_1, $PM_{2.5}$ and PM_{10})

        iii. ability of the technologies to characterise the particulate matter

        iv. the applicability of these technologies to the rail corridor, including issues such as robustness to external conditions such as weather, whether a standard technology as used by USEPA/NSW EPA monitoring guidelines, cost, multi/single purpose function, and ability to be remotely used

        v. typical placement /deployment of the technologies including co-location

d. Discuss any other issues related to this topic and any other comment you believe is relevant

5. The Information Paper should ideally be a maximum of 30 pages in length (excluding appendices). The Information Paper must be delivered electronically in Word format; be fully referenced and contain suggestions for further reading for those interested in gaining a more detailed understanding of the subject.