The Use of LiDAR in Measuring Airborne Particulates – A Technical Review of LiDAR Trials in Port Hedland

Technical Review

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Term	Meaning
AHD	Australian Height Datum
ASL	Above Sea Level
BHP	BHP Billiton Iron Ore Pty Ltd
BoM	Bureau of Meteorology
ConsMin	Consolidated Minerals
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
DWER	Department of Environment and Water Regulation
EPA	Environmental Protection Authority
EP Act	*Environmental Protection Act 1986*
ETA	*Environmental Technologies & Analytics Pty Ltd*
Fortescue	*Fortescue Metals Group*
km	kilometres
LiDAR	Light Detection and Ranging
m	metres
min	minutes
ML	Mining Lease
Mt	Million tonnes
Mtpa	Million tonnes per annum
PHIC	Port Hedland Industries Council
PM	Particulate Matter
PM2.5	Total of suspended particulate matter less than 2.5 µm in aerodynamic diameter
PM10	Total of suspended particulate matter less than 10 µm in aerodynamic diameter
PPA	Pilbara Ports Authority
TSP	Total Suspended Particles
WA	Western Australia
µm	microns
$\mu g/m^3$	Micrograms per cubic metre

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Figures

1 Introduction

Port Hedland Industries Council (PHIC) commissioned Environmental Technologies & Analytics (ETA) to undertake an independent technical review of the use of Light Detection and Ranging (LiDAR) technology as a particulate (dust) measurement technique, specifically in the context of Port Hedland, Western Australia. As part of this review, ETA contracted Dr John Holdsworth from the University of Newcastle to provide commentary on the LiDAR studies that have previously been undertaken in the Port Hedland region. The review also considered the limitations and opportunities in using LiDAR in the Port Hedland context, based on the reported findings of the previous studies.

To date three studies have applied LiDAR technology to assess dust in Port Hedland. These studies have been carried out by researchers, government and industry for varying purposes. The studies include:

- CRC CARE (2011)
- PHIC LiDAR study (December 2014 – March 2015 and September 2015 – March 2016)
- Department of Water and Environment Regulation (DWER) (2017)

All three of the studies reviewed undertook some form of calibration of the LiDAR backscatter to the ambient monitoring data in the region with the aim of deriving a correlation factor.

PHIC acknowledges that LiDAR is a useful tool or technique, however the studies to date have identified specific limitations, which appear to be exacerbated where there are multiple dust sources, as in the case of Port Hedland. The purpose of this review is to facilitate a common understanding and to provide a sound technical basis for future studies that could include the use of LiDAR technology.

2 Background – Sources of Dust in Port Hedland

Port Hedland is a coastal town in the Pilbara region of Western Australia. The Port of Port Hedland is the largest bulk materials port in the world, with an annual export tonnage exceeding 500 million tonnes (Mt) per annum. Approximately 97 per cent of exports from the port comprises iron ore.

To assist in developing an integrated approach to air quality and other potential cumulative industry issues, such as noise, the Port Hedland Industries Council (PHIC) was established in 2009. PHIC is comprised of key port users including BHP, Fortescue, Roy Hill, Pilbara Ports Authority (PPA), Consolidated Minerals and Mineral Resources. The location of the key export facilities in the region are presented in Figure 2-1.

There are numerous sources of particulates in the Pilbara region ranging from anthropogenic (resulting from human activity) to biogenic (resulting from natural sources). The following sections broadly outline the sources of these various particulates in the context of Port Hedland the broader Pilbara region.

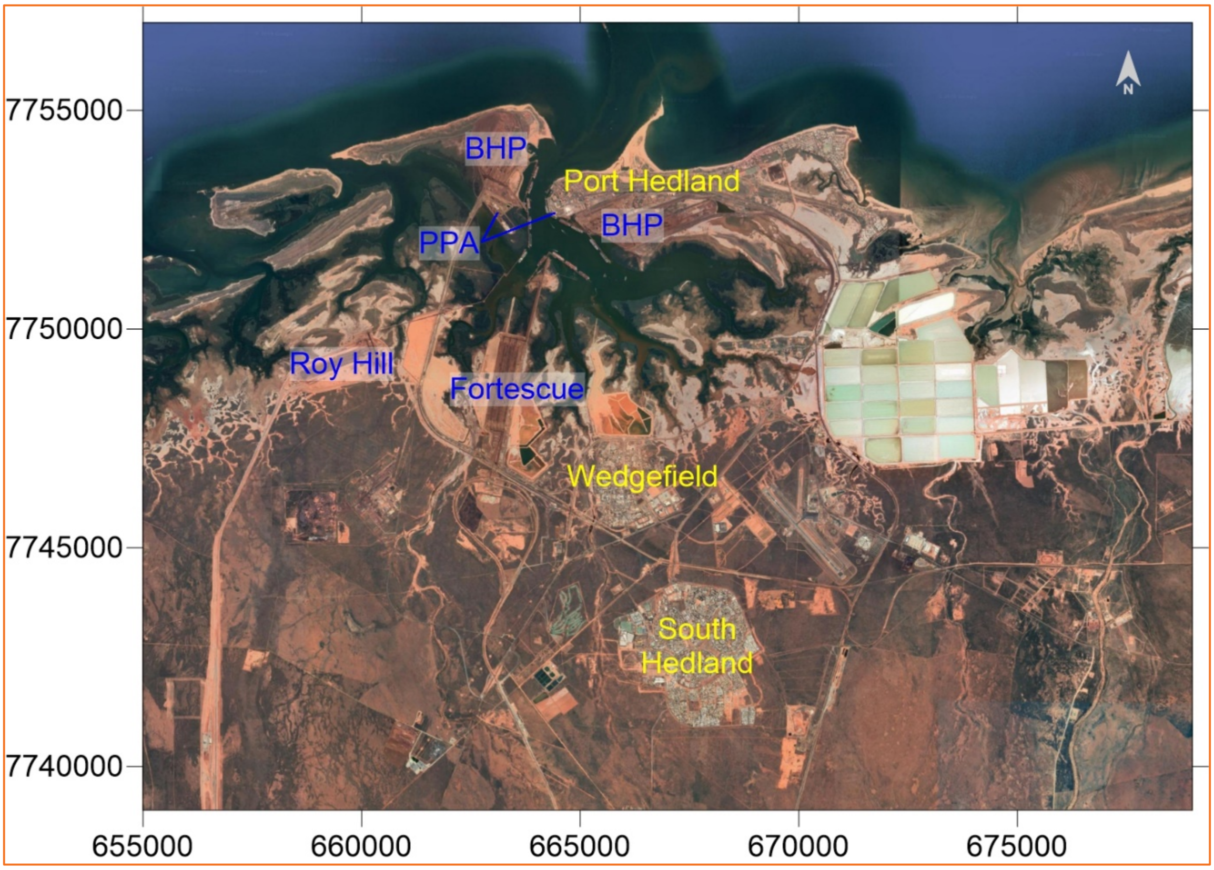

Figure 2-1: Export facilities, Port Hedland, Western Australia

2.1 Particulates Sources

As outlined by the Californian Air Resource Board (CARB) particulate matter (PM) is not a single pollutant but is a combination of many elements including suspended solids and liquids (CARB, 2020). There are multiple sources of PM include biogenic (natural) such as sea salt, pollen, wildfires, and dust storms and anthropogenic (human made) which includes industrial sources (point and fugitive), combustion sources (vehicular, power generation and shipping) and construction/landfills. Dust is commonly used as a replacement for PM though it is more accurately refers to particles that are derived from the mechanical breakdown of rock, soil and biota.

Concentrations of particles suspended in air can be classified by an aerodynamic diameter, which describes the behaviour of the particle in the air based on its size and shape. The classification is described as:

- Total Suspended Particulate (TSP) – refers to the total amount of the PM suspended in air (regardless of size). Particles in air are subject to gravitational settling; particles larger than about 30 µm in aerodynamic diameter are likely to be removed by gravitational settling within a short time of being emitted (i.e. they settle to the ground or other surfaces fairly quickly). These larger particles are primarily associated with amenity or visibility issues.
- PM_{10} refers to the total of suspended particulate matter less than 10 µm in aerodynamic diameter (inclusive of $PM_{2.5}$). Particles within the range of $PM_{2.5}$ – PM_{10}, in the Port Hedland region, are outlined in Section 2.1.1 and include industrial (material handling) and commercial (concrete batching, metal fabrication). Particles in this size range can enter bronchial and pulmonary regions of the respiratory tract and can impact human health. Particles in this size range can remain suspended for many days in the atmosphere.
- $PM_{2.5}$ refers to the total of suspended particulate matter less than 2.5 µm in aerodynamic diameter. Particles in this size range tend to be dominated by combustion related sources such as wildfires, residential wood burning, power generation, and vehicles. Epidemiological studies have shown that particles in this size range are associated with greater health impacts on humans than other particle sizes. These particles can remain suspended for months to years.

2.1.1 Port Hedland

Sources of particulates within the Port Hedland airshed can be divided into four broad categories:

- Industrial: Includes all material handling processes undertaken within the BHP, Fortescue, Roy Hill and PPA operations:
    - Car dumping or truck unloading
    - Stacking
    - Reclaiming
    - Shiploading
    - Material transfer including transfer stations and conveyors
    - Wind erosion of exposed surfaces (eg. stockpiles)
    - Shipping
    - Vehicle activity within the facility
- Commercial: Sources within this classification include all non-industrial sources particularly those contained within the Wedgefield light industrial estate which includes:
    - Concrete batching plant
    - Metal recycling facilities
    - Transport companies
    - Metal fabrication

  There are also additional commercial areas within the airshed including along Redbank and within the west end of Porth Hedland itself.
- Residential: Although not a major contributor to particulates in the Port Hedland airshed emissions from these sources include, but not limited to:
    - Vehicle traffic from both sealed and unsealed roads (inclusive of emissions from the exhaust, brakes and tyres)
    - Lawnmowing

    - Wood fires (barbeques)
    - Recreational boating
- Biogenic: Emissions from biogenic sources can be highly variable (spatially and temporal) and include:
    - Sea salt
    - Wind erosion of exposed surfaces
    - Wildfires

It is important to note that both wind erosion and wildfire can, and do, result in some of the highest daily ground level concentrations of particulates recorded in the region (SKM, 2000).

2.1.2 Regional

The Pilbara region of Western Australia is classified, according to the Koppen-Geiger system, as BWh (hot desert) and has two primary seasons – wet and dry. The wet season, from October to April, is dominated by high temperatures and evaporation rates with isolated intense rainfall and cyclonic activity. The dry season, from May to September, is relatively dry with mild temperatures.

The Pilbara region is a naturally dusty environment with wind-blown dust being a significant contributor to the particulate loading. Within the aggregated emission inventory for the Pilbara, undertaken by SKM in 2000 for the 1999/2000 financial year, it was calculated that approximately 170,000 tonnes (as PM_{10}) was emitted as a result of wind erosion from erodible areas (excludes mining/port operations). Another significant source is wildfires which account for approximately 195,000 tonnes of particulates (as PM_{10}) emitted. Note that both estimates are calculated and will vary on an annual basis depending on a range of factors including – extent of erodible areas, area burnt, rainfall and wind speed.

To gain an understanding of the causes of these high emissions, especially from wildfires, the fire scar data for parts of the Pilbara region from 2016 to 2018 is presented in Figure 2-2. From this figure it is apparent that large areas are burnt every year, with the majority of these fires starting due to natural processes namely lightning strikes. Once an area is burnt it is highly susceptible to wind erosion resulting in large, regional scale dust storms (Figure 2-3).

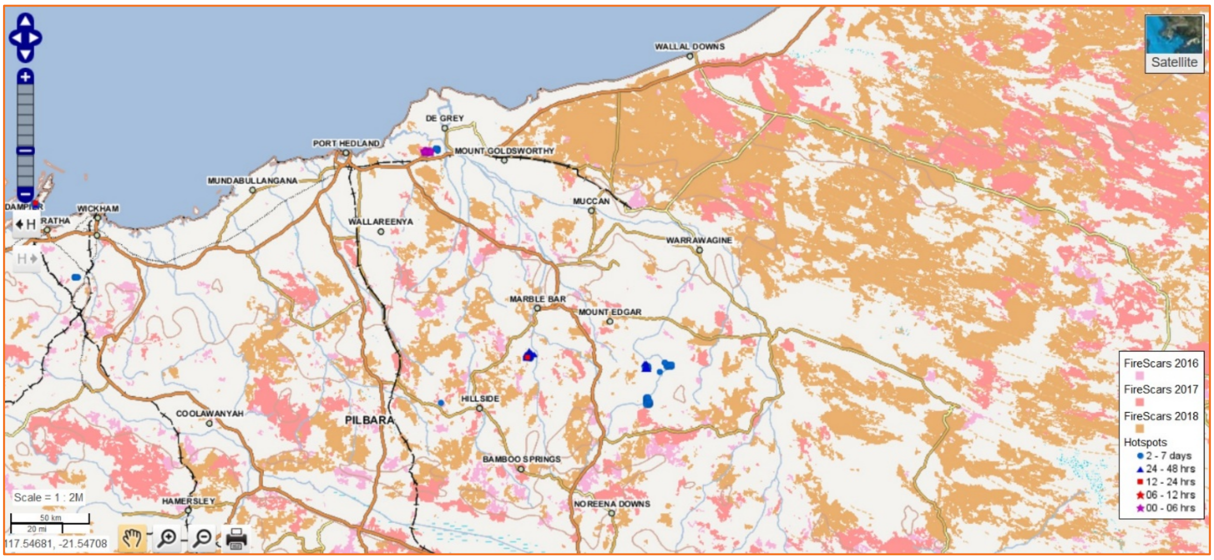

Figure 2-2 Fire Scar data for the Pilbara (2016 – 2018) (Firenorth, 2019)

Figure 2-3 Dust Storm in the Pilbara (Flikr, 2019)

3 LiDAR

3.1 What is LiDAR?

LiDAR is an acronym for 'Light Detection and Ranging'. LiDAR was developed in the early 1960's and since then has proven to be an extremely versatile technology used for a wide variety of purposes including remote sensing, vehicle automation and atmospheric studies.

3.2 How does LiDAR work?

The basic principle behind a LiDAR is relatively simple – the instrument (transmitter) releases rapid pulses of laser light along a path (to a receiver) and measures the time it takes for each light pulse to return. Simply stated a LiDAR works on the same principle as RADAR, except that it uses a laser beam. In reality, the process is a little more complicated. The laser pulse will be attenuated (reduction in signal strength) by absorbing particles in the atmosphere, reflected from larger particles such as fog, rain, dust etc, scattered from smaller aerosols. The light that hasn't been affected by these impacts, just keeps going (Holdsworth, 2019). An example of this process is presented in Figure 3-1 which shows the beam along a single pathway which is a common sampling methodology for vertical studies such as boundary layer height determination (Luo T. et. al, 2014) and cloud heights (Martucci, G., et. al, 2009 & Picket, M., 2018). For the studies undertaken in Port Hedland the LiDARs were operated by scanning for a full circle (Section 5.3), which is similar to how a lighthouse is operated.

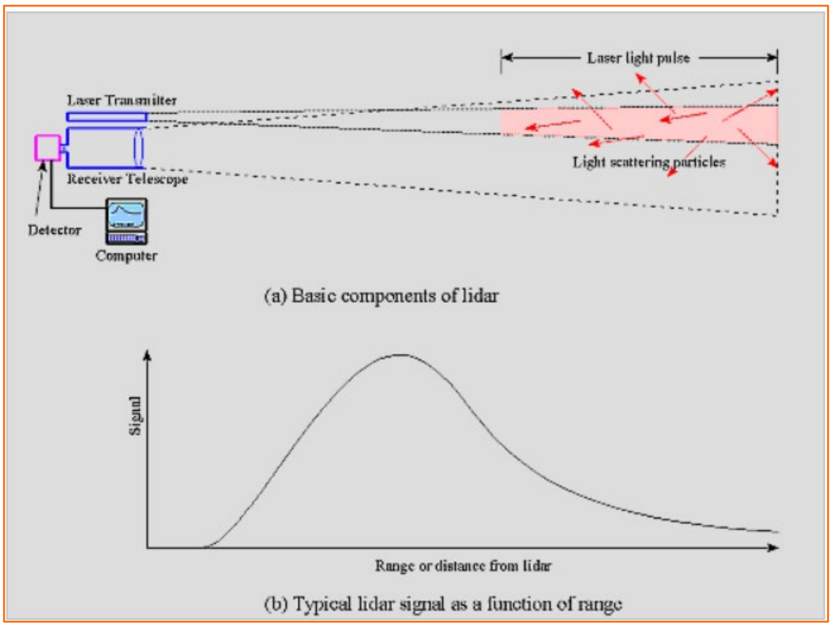

Figure 3-1 Example of beam from a LiDAR (NOAA, 2019)

As outlined in Pickett (2018), the range in which in a LiDAR can be expected to return a signal is dependent on the energy of the initial pulse and the size of the telescope aperture for the returned signal. Large 'research-grade' LiDARs are designed for large distances, as such the unit is relatively large and cumbersome to locate. An example is the LiDAR utilised by the Arizona State University during the Department of Environment and Conservation (DEC – now DWER) *Wagerup Winter 2006 Intensive Air Quality study* which was mounted on a prime mover trailer (DEC, 2007). Micro LiDARs, similar to the ones utilised previously in Port Hedland (Section 4), are designed for distances out to 5 – 6 kilometres (km) and the newer 'Pocket LiDARs', which are designed for specific purposes such as vehicle detection, tend to have a range of less than 1 km.

As explained in Holdsworth (2019), the goal of atmospheric LiDAR studies is to develop an understanding of the optical behaviour of the atmosphere being studied by apportioning the distribution of the pulse energy to the reflection, absorption, transmission and scatter at each step of the light path into the atmosphere and on the path back to the detector. Accurate apportionment of the energy loss requires knowledge of each of these competing processes at each step of the optical pathway. These competing processes cannot be known definitively with a simple LiDAR system. LiDAR systems that use a single wavelength have embedded assumptions about the relative magnitudes of each of the contributing effects with distance, temperature, or particle size and concentration.

If the atmosphere is homogeneous and transmittance is 100%, then the backscattered signal is largely proportional to the total suspended particulate concentration, or aerosol loading, of the atmosphere. Hence in most LiDAR studies, there is an apparent correlation between PM_{10} concentrations as measured by other devices and the LiDAR return signal. The assumption that LiDAR is measuring PM_{10} concentration is not correct. A LiDAR can map the extent and location of a dust plume in *relative* terms in real-time and it is recognised as the only practical measurement technique to allow real-time two or three-dimensional mapping of a plume or to map the vertical extent of a plume.

Another important factor with LiDAR is data presentation – how to present the attenuated backscatter, in a clear and concise format, while taking into account the factors listed previously. This is a complex process that is undertaken by specifically designed software. However, it will always have to make some assumptions regarding aerosol shape, composition, size and varying concentrations along the beam length.

When using a LiDAR for atmospheric studies there are two main types – coherent and direct detection. A coherent LiDAR, is also known as a Doppler LiDAR as it measures the doppler shifts by comparing the frequency of the returned signal to a reference beam, while the direct detection LiDAR measures the frequency shift by passing the returned light through an optical filter (Slinger, C & Harris, M, 2019).

Western Australia has a strong history of using LiDAR for atmospheric pollutant studies commencing back in 1998 when a LiDAR was used to investigate the plumes from power stations within the Kwinana Industrial Estate (Sawford, B. et. al., 1998) followed by the Wagerup study in 2006 (DEC, 2007) and subsequent investigations at Point Samson, Port Hedland and Mandogalup. Studies have been undertaken elsewhere in Australia, primarily in the Hunter Valley of New South Wales (NSW), though these studies primarily used a single direction LiDAR as opposed to a full 360^{o} scan that has been used in WA.

4 Previous Studies within Port Hedland

Within the Port Hedland region, three LiDAR studies have been initiated including:

- CRC CARE – 2011
- PHIC – (December 2014 – March 2015 and September 2015 – March 2016)
- DWER – 2017

An outline of each of these studies is contained within Table 4-1.

Table 4-1: Purpose, and findings, of each LiDAR study

	CRC Care	PHIC (Leosphere / Ecotech)	DWER
Timing / Duration	August – September 2011 (3 weeks)	1st survey: December 2014 – March 2015 (4 months) 2nd survey: September 2015 – March 2016 (7 months)	February – June 2017 (5 months)
Partners		Leosphere (now Viasala) and Ecotech	Ecotech
Equipment	Doppler Windimager (Halo Photonic)	Doppler Windcube 200S (Leosphere)	Doppler Windcube 200S (Leosphere)
Location	PPA Control Tower	Fortescue Surge Bin	Town of Port Hedland viewing tower
Elevation	32m ASL	36m ASL	25m ASL
Field of view	Due to blind spots the unit was relocated several times during survey. Covered the BHP and PPA operations and Fortescue shiploaders (no stockpiles)	BHP, Fortescue, PPA and Roy Hill operations. Also included Wedgefield	BHP and PPA operations, Fortescue shiploaders and 50% of the stockpiles. Only covered the Roy Hill shiploader (not actual operational area). Did not include Wedgefield.
Sampling angle	1° arc	2° arc	1° arc
Aim	Demonstrate the performance of coherent doppler LiDAR in: • Identifying key emission sources • Tracking plumes • Measuring dust concentrations within the plume • Investigating fine scale wind fields	1st survey: Testing LiDAR as a tool to measure air bourne dust and demonstrating the ability of LiDAR to identify dust hot spots 2nd survey: Assessing the performance of LiDAR across seasonal variations	Determine the origins and movement of dust contributing to impacts within, and around, Port Hedland.

	CRC Care	PHIC (Leosphere / Ecotech)	DWER
Findings	The general findings of the study were that LiDAR is suitable for potentially identifying emission sources and tracking dust plumes. LiDAR has the ability to resolve fine scale wind field dynamics	The general findings were that the units performed well across seasonal variations though changes in atmospheric conditions required the unit to be recalibrated. LiDAR can detect plumes and highlight the direction of travel though issues with the resolution did impact hot spot identification at distances.	DWER undertook an analysis of each excursion of the Taskforce criteria (70ug/m^3 over 24 hours) at the PHIC monitors (Richardson St, Kingsmill St and Taplin St). DWER determined that there was a high correlation between the LiDAR and monitored concentrations – providing a level of confidence that the LiDAR is representing the particle loading.

5 Review of Previous LiDAR Studies in Port Hedland

A review of each of the studies outlined in Table 4-1 was undertaken by Dr John Holdsworth from the University of Newcastle with the aim of determining the appropriateness and validity of relying upon LiDAR as a monitoring tool for ambient dust measurement. There are a few critical points to understand in regard to these studies including:

- Scanning height of the LiDAR
- Sampling angle
- Wind speed
- Data presentation
- Calibration to Australian Standard monitors

Each of these points is outlined in the following sections.

5.1 Scan height

The review noted that all three of the projects were undertaken with a 2-dimensional (2D) scan on a horizontal plane. As such it is important to note that the return signal would only be monitoring either:

- Elevated sources, or
- Plumes that had reached the scan height of 25-36m.

There are numerous elevated sources within the region including car dumpers, stackers, reclaimers, shiploaders and exhaust vents from scrubbing systems (wet and dry). The impact that these sources potentially have on the LiDAR scan is presented in Figure 5-1. From this figure it can be seen that the exhaust stream from the scrubbers would almost immediately intersect the LiDAR scan, while emissions from the stackers (along with the reclaimers and shiploaders) would also intersect the LiDAR scan either immediately or very close to the source depending on the atmospheric conditions at the time of sampling.

The emissions from lower or ground level sources, such as conveyors and vehicles, may not intersect the LiDAR scan height until some distance downwind. A broad example of this is outlined in Figure 5-2 which presents a plume moving downwind (away from the point of emission) and gradually rising. In this example, the elevated LiDAR scan only intersects with the plume at a distance downwind of the source. This greatly increases the complexity of inferring the potential source of that plume, particularly when there are multiple sources.

These factors result in two main implications for interpreting the results of an elevated LiDAR scan:

- Plumes from elevated sources being over-represented in the LiDAR scan giving the skewed impression that these are the only dominant sources within the airshed.
- Plumes from ground level sources being ignored, or underrepresented, as the plume either:
    - does not reach the height of the LiDAR scan
    - becomes 'diluted' with height and distance downwind
    - the potential for plumes from co-located sources merging.

It should also be noted that the atmosphere is a 3-dimensional (3-D) space with complex turbulent flows depending on a range of factors including (but not limited to), temperature, solar radiation, cloud cover, wind speed, topography and land use. A simple 2-D scan, as presented in Figure 5-2, may not provide an accurate representation of source locations.

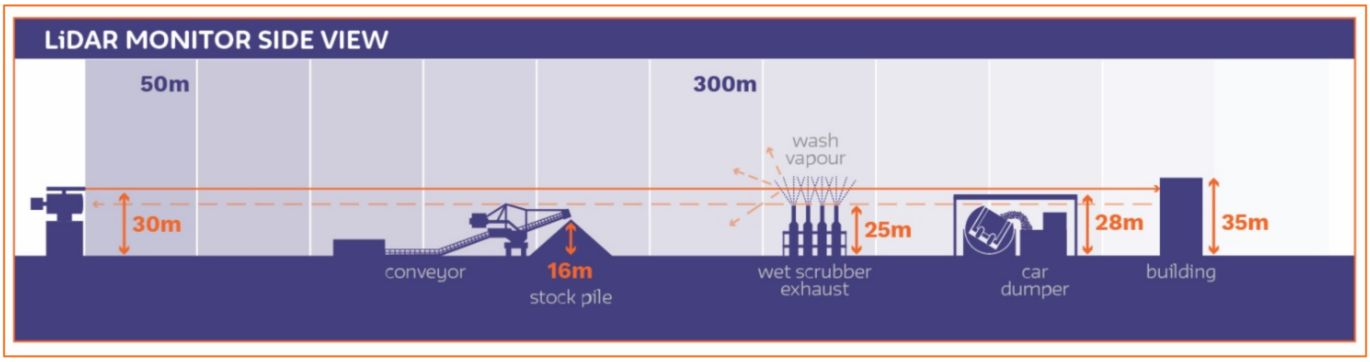

Figure 5-1: Example of LiDAR scan height with various potential sources within the airshed

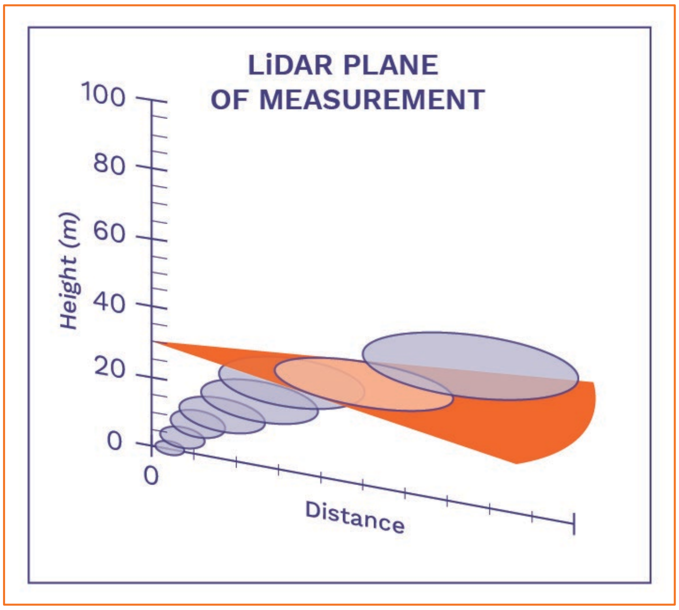

Figure 5-2: Example of scanned plume

5.2 Wind speed

Another factor that needs to be considered is the wind speed, specifically the increase in wind speed with height – commonly known as the wind speed gradient. At ground level, the wind speed is reduced due to increased friction of obstacles such as rocks, trees and buildings - commonly referred to as the surface roughness. An example of the wind speed gradient, under stable atmospheric conditions, is presented in Figure 5-3. From this figure it is evident that the wind speed at 100m is higher than the corresponding wind speed at 10m. This variation in the wind speed also exists at the height of the LiDAR scans (Section 5.1) and care must be taken when attempting to extrapolate wind speeds from heights at 25 – 30 m to ground level. This is because the wind speed at the surface can be significantly slower than the wind speed at the height of the scan.

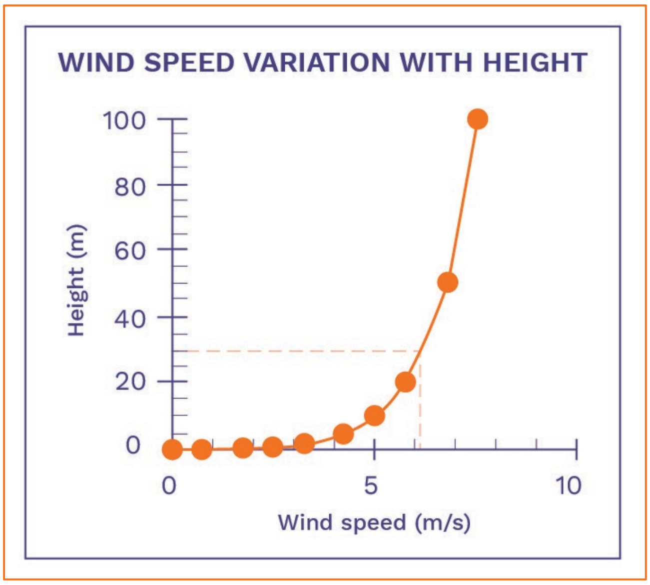

Figure 5-3: Example of a wind speed gradient

5.3 Sampling

As outlined in Section 4, all three studies were undertaken for a full 360 degree with a sampling angle of one degree in the CRC CARE and DWER studies and two degree in the PHIC study. A full 360 degree sweep, or cycle, takes 10 minutes (min) which means that for the CRC CARE and DWER projects each one degree arc was analysed for 2 seconds every 10 min or 12 seconds every hour. Within each one degree arc the LiDAR records the backscatter for a distance of approximately 20m increments – this arc/distance is known as a gate-degree (an area of one degree by 20m). As the distance from the LiDAR increases the area contained within a gate-degree also increases, which decreases the spatial resolution. For example, at 500m from the LiDAR the area covered by a gate-degree is approximately 170m^2, while at 3,000m from the LiDAR the area covered by a gate-degree is approximately 1,070m^2.

5.4 Data Presentation

As outlined in Section 3.2, a critical component of LiDAR studies is the presentation of the data. There are numerous factors which can impact the signal recovery including:

- temperature,
- relative humidity,
- particle type and size, and
- particle concentration.

The review of the three studies currently undertaken within Port Hedland determined that only the Leosphere / Ecotech (PHIC) and DWER studies discussed the data visualisation process. This report stated that they utilised the software package 'Windforge' which is the generic software provided with the Leosphere Windcube LiDAR (noting that as the PHIC and DWER studies utilised the same LiDAR it can be assumed that the software, and process, is similar). The actual algorithms used to process the data are not disclosed and there are issues with the lack of transparency in the data handling process. This is highlighted in the statement that, in relation to rings appearing on the radial plot display, '*Manual data processing is used to calculate a revised set of calibration constants for the LIDAR to eliminate the effect*'. While understanding the complexities of signal recovery from LiDAR data, this is an extraordinary statement that the code is adjusted to make the Plan Position Indication (PPI) (horizontal scan) look good on the web.

The Leosphere / Ecotech report also states that '*The background aerosol was not shown in the end of the campaign B maps as the actual dust plumes are the important part to be visualised*'. This effectively means that the results have been adjusted to highlight the anthropogenic plumes rather than show the natural aerosol load existing in the region. The adjustments include plumes shown as 'solid' which is inappropriate as there are LiDAR return from aerosols further away than the 'solid' band of aerosols.

5.5 Calibration

All three of the studies reviewed undertook some form of calibration of the LiDAR backscatter to the ambient monitoring data in the region with the aim of deriving a correlation factor. Within the region PHIC operates a series of Beta Attenuation Monitors (BAM) as prescribed by an Australian Standard (AS/NZS 3580.9.11:2008). The DWER study simply undertook a correlation between the LiDAR and BAM to derive a correlation to assist in evaluating the LiDAR as a tool for tracking dust plumes. The CRC CARE and Leosphere / Ecotech studies attempted to use the derived correlations to convert the LiDAR signal into a mass concentration. The issues with undertaking this analysis include:

- **Height:** As discussed in Section 5.1, the scan heights from the various LiDAR studies varied from 25 – 36m above the surface while the inlet tubes for the BAM's are only 3-4m above the surface. This means that the LiDAR is recording a return signal at a minimum height of 21m above the BAM.
- **Wind speed:** As outlined in Section 5.2, the wind speed at the scan height will be greater than the wind speed recorded at ground level by a BAM monitor. Wind speed measurements are often taken at 10m. However, this will not negate the difference between the measurement technique or result.
- **Timing:** The BAM units utilised by PHIC are the MetOne BAM1020 units which record a PM_{10} concentration over an hour. As discussed in Section 5.3, the LiDAR units are undertaking a full 360 degree scan every 10 minutes meaning that the LiDAR is only scanning above a BAM unit for 12 seconds every hour.
- **Area:** As outlined in Section 5.3, the LiDAR units are monitoring an area of one degree by 20m which can be considered to be the spatial resolution of the signal, whereas a BAM unit is monitoring from a specific point at the height of the monitoring inlet.

Taking these factors into consideration, the assumption that a LiDAR can be calibrated to, or is measuring, PM_{10} concentrations is an inaccurate representation of the data comparison process that can be achieved. This is therefore considered an incorrect interpretation in the studies where this is applied. Any attempt to correlate the LiDAR measurements with BAM measurements needs to be undertaken in such a way as to account for the fundamental differences in the two techniques, and the studies referencing the BAM comparison to date have not dealt with this issue in a thorough or technically reliable manner.

5.6 Overall Position

During the review process of the LiDAR studies previously undertaken in the Port Hedland region it became apparent that all three studies had approximately similar objectives – namely evaluating LiDAR as a tool for determining the sources of dust (or hotspots) and tracking their pathways within the airshed.

The review of these reports determined that the general objectives have been met with the finding that '*The LiDAR unit is very capable in tracking dust plumes, if so configured and controlled*'.

Basically, this indicates that LiDAR is excellent at showing relative backscatter maps and there is a clear preference by the reviewers to stay with this simplistic approach than to attempt to apply a calibration to convert the results to mass concentrations. It is also essential that the limitations of LiDAR's, as outlined briefly in this review, be taken into account when undertaking future studies.

It should also be noted that, with respect to atmospheric monitoring, there is no Australian Standard for the operation of a LiDAR system and as such, there is the potential for variations in the installation, operation, maintenance and data processing and visualisation between different installations and systems.

6 Conclusion

The review of the three LiDAR trial conducted in port Hedland between 2011 and 2017 determined that, as a measurement technique of air quality, it is capable of visually representing, or mapping, the extent and location of a dust plume in *relative* terms in real-time. It is the only practical measurement technique currently available to allow real-time two or three-dimensional mapping of a plume or to map the vertical extent of a plume.

It should also be noted that, with respect to atmospheric monitoring, there is no Australian Standard for the operation of a LiDAR system and as such, there is the potential for variations in the installation, operation, maintenance and data processing and visualisation between different installations and systems.

The general findings of the review of all three projects are outlined below:

Scan height

- A simple 2-D scan may not provide an accurate representation of source locations as the atmosphere is a 3-D space with complex turbulent flows depending on a range of factors.
- Plumes from elevated sources being over-represented in the LiDAR scan giving the skewed impression that these are the only dominant sources within the airshed.
- Plumes from ground level sources being ignored, or underrepresented, as the plume either:
    - does not reach the height of the LiDAR scan
    - becomes 'diluted' with height and distance downwind
    - the potential for plumes from co-located sources merging.

Wind speed

- The wind speed increases with height – so the wind speed (and potentially the wind direction) is higher at the LiDAR scan heights than the 10m meteorological measurements.

Sampling

- Due to the measurement methodology each full 360 degree scan of the LiDAR takes 10 minutes, allowing for 2 seconds for every one degree arc.
- As the distance from the LiDAR increases the area contained within a gate-degree also increases, which decreases the spatial resolution.

Data presentation

- There was limited information to determine the process of converting the raw data into a visual scan.
- There were incidences of the code being adjusted to improve the visual representation
- The results were adjusted to highlight the anthropogenic plumes rather than show the natural aerosol load existing in the region

Calibration

- Attempts to calibrate the LiDAR signal to a mass balance, from a correlation with ambient monitoring data, are erroneous.

7 References

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